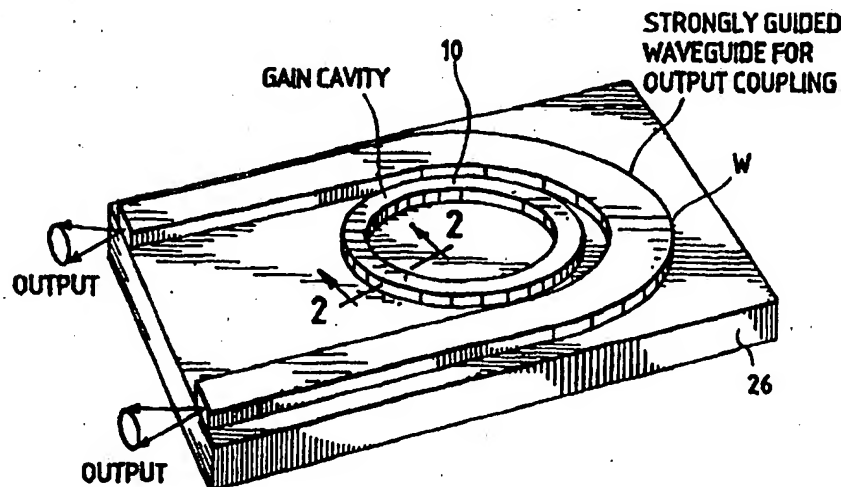




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(54) Title: PHOTONIC WIRE MICROCAVITY LIGHT EMITTING DEVICES



(57) Abstract

A photonic light emitting device comprising a relatively high refractive index photonic-wire semiconductor waveguide core in the form of an arcuate shape, linear shape and combinations thereof. The waveguide core is formed into a closed loop cavity for a light-emitting device or laser. The waveguide core is surrounded on all transverse sides by relatively low refractive index medium (23) and comprises an active medium (30) having major and minor sides and semiconductor guiding layers (32a, 32b) proximate the major sides. The active medium and the guiding layers are so dimensioned in a transverse direction relative to the path of light propagation through the core to provide dramatically increased spontaneous-emission coupling efficiency, leading to low lasing threshold and high intrinsic modulation rates.

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PHOTONIC WIRE MICROCAVITY LIGHT EMITTING DEVICES

5 This application is continuation-in-part of
Serial No. 08/450,284 filed May 25, 1995.

CONTRACTURAL ORIGIN OF THE INVENTION

10 This invention was made with Government
support under Grant Number; ECS-9502475 awarded by
the National Science Foundation and Grant Number:
F30602-94-1-003 awarded by the Advanced Research
Project Agency of the Department of Defense. The
Government may have certain rights in the
15 invention.

FIELD OF THE INVENTION

20 The present invention relates to a light
emitting device or laser and, more particularly,
to a photonic-wire microcavity light emitting
device or laser having high stimulated emission
and hence gain and capable of high conversion
efficiency from pumping power to optical output.
When operated as a laser, it can have low lasing
25 threshold. Other advantages include extremely
high near-ideal photon emission efficiency into
the electromagnetic field mode of interest, small
physical size, and high intrinsic modulation rate
when operated above the lasing threshold. In
30 addition, it can be coupled directly to strongly-
guided waveguides, making it suitable for
application to very-high-density photonic
integrated circuits.

BACKGROUND OF THE INVENTION

Microcavity semiconductor lasers recently have been described for operation. Such microcavity semiconductor lasers employ an active lasing medium that support optical modes in a short cavity. For example, a microdisk laser is described by McCall et al. in "Whispering-gallery mode microdisk lasers" in Appl. Phys. Lett. 60, (3), 20 January 1992. Such microcavity laser supports the electromagnetic field mode in a thin disk on top of a small supporting pillar.

Microcavity semiconductor lasers are advantageous as compared to conventional semiconductor lasers in being much smaller in size and requiring substantially less minimum operating current (power) in the range of microwatts. Recently, in "Directional light coupling from microdisk lasers", Appl. Phys. Lett. 62, 561 (1993) an asymmetric point was introduced into a microdisk to provide a location of increased quantity of lasing light to leak out from the point of asymmetry. Light emitted from such a thin disk with thickness d from the asymmetric point can undergo a large angle of diffraction in the directions perpendicular to the disk plane. According to the physical law of diffraction, the diffraction angle is given by $\Theta = 2 \cdot \text{ArcTan}(\lambda/d)$ in radians and will occur at a distance of $2\pi d^2/\lambda$ away from the edge of the disk. The thin disk of thickness around 0.2 micron emitting at a wavelength of 1.5

microns will give rise to a diffraction angle of $\Theta = 2.88$ radians or almost 165 degrees and will occur at 0.15 micron from the disk's edge. This means that the light emitted from the disk will disperse away rapidly within a short distance of less than two tenths of a micron, which makes it very difficult, if not impossible, to collect a useful fraction of the output laser light into a semiconductor waveguide in practice.

Microdisk lasers can have high efficiency (with a spontaneous-coupling factor of larger than 0.1) only in the limit of small disk radius of 1-1.5 microns for the emission wavelength of 1.5 microns. The required disk radius scales linearly with the optical wavelength. This makes it very difficult to realize an efficient microdisk laser at short wavelength range, such as the visible wavelength of 0.5 microns. Visible microcavity lasers are important as they have applications to color display or high-density optical storage or sensing. According to the above scaling rule, at the visible wavelength of 0.5 microns, an efficient microdisk will need a disk radius of 0.3-0.5 microns and will be difficult to fabricate and suspend on a pillar.

The difficulty of obtaining useful light from microdisk lasers and their small disk size needed for high cavity efficiency make it difficult to use microdisk lasers in many practical applications.

An object of the present invention is to provide a photonic-wire light emitting device or

laser which has an extremely high spontaneous-emission coupling efficiency or factor of for example 0.3 and larger by virtue of use of a photonic-wire waveguide core combined with microcavity structure and which can be scaled to operate at the visible wavelength range without the aforementioned problem.

Another object of the present invention is to provide a photonic-wire microcavity light emitting device or laser amenable for coupling light out from the device to, for example, a semiconductor waveguide efficiently because of its extremely high spontaneous-emission coupling efficiency or factor. In addition, the photonic-wire laser can be modulated at very high modulation rate, which will enable high data transmission in a photonic circuit.

Yet still another object of the present invention is to provide a photonic-wire microcavity light emitting device or laser amenable for coupling light out from the device to a strongly-guided semiconductor waveguide, making it amenable for coupling to very-high density integrated optical circuits connected by such waveguides. Such strongly-guided waveguides can make bends of smaller than 1 micron radius with negligible photon loss, making it possible to integrate 1000 or more optical components within a 1 millimeter square area and resulting in very-high density photonic integrated circuits. Furthermore, the photonic-wire device can be integrated via direct fabrication on a wafer

instead of via hybrid integration. Such very-high density photonic integrated circuits will have applications to optical communications, optical interconnects, optical sensing, optical signal processing, and optical computing.

In comparison, conventional integrated optical circuits are typically made up of hybrid optical components consisting of semiconductor lasers with long cavity lengths of 300 microns (0.3 millimeters). The laser components are coupled to weakly-guided ridge waveguides. A weakly-guided waveguide cannot make a bend with a radius smaller than a few millimeters without incurring very high photon loss because of radiation from the bend. This seriously restricts the integration density of the current typical integrated optical circuits to at most a few components in a millimeter square area.

Yet still an additional object of the present invention is to provide a highly efficient cavity for applications to visible semiconductor laser light sources or light-emitting diodes (LEDs) with edge emission, which are difficult to realize at present due partially to the low efficiency of conventional cavity designs.

SUMMARY OF THE INVENTION

The present provides a photonic-wire light emitting device or laser comprising a relatively high refractive index photonic-wire waveguide core which is surrounded in all directions transverse to photon propagation direction, such as, for

example, both in a width direction and thickness direction, of the waveguide core by relatively low refractive index medium, such as air, silica or other relatively low refractive index material, to spatially confine photons strongly in all directions perpendicular to their propagation direction in the waveguide core. The waveguide core comprises an optically active excitable medium (hereafter referred to as active medium), which can give rise to radiation or absorption of electromagnetic field energy, and in particular gain or luminescence. The active medium is bordered on the major sides by guiding semiconductor layers. The active medium typically comprises layers of semiconductor quantum wells or excitable rare earth ions. The active medium and guiding layers are so dimensioned in transverse directions relative to the path of light propagation through the waveguide core as to provide greatly increased spontaneous-emission coupling efficiency for photons emitted by the quantum wells into a particular electromagnetic field mode of interest.

The present invention provides in an embodiment a light emitting device having $\text{Beta}(\text{tot})$ much larger than that available from conventional semiconductor laser cavity design and from which a working device can be realized. For example, a typical prior semiconductor laser cavity with a 300 micron long linear cavity defined by a ridge waveguide exhibits a $\text{Beta}(\text{tot})$ value of about 0.00001 for a $\text{Beta}(\text{Space}) = 0.004$

and $\text{Beta}(\text{Freq}) = 0.003$. The present invention provides a light emitting device having a $\text{Beta}(\text{tot})$ which can be as large as 0.3 and higher achieved through combined use of photonic-wire waveguides, microcavity structure, and an appropriate active medium, such as quantum wells.

A particular photonic-wire light emitting device in accordance with an embodiment of the present invention comprises a relatively high refractive index photonic-wire semiconductor waveguide core. The photonic-wire waveguide core is formed into an arcuate shape, linear shape and combinations thereof. As described in more detail below, when the photonic-wire waveguide is closed onto itself, forming a close loop cavity, a high Q and high gain cavity is provided. The high Q cavity can be an efficient cavity for the light-emitting device or laser and, in particular, can be a lasing microcavity.

The high refractive index semiconductor waveguide core is surrounded by relatively low refractive index medium on all sides. This confines photons tightly in directions perpendicular to their direction of propagation. The strong confinement forms strong confining potential walls for photons, and the waveguide is called a photonic-wire waveguide. The strong potential is necessary to affect the emission properties of the active medium of the waveguide, and can be used to dramatically increase the percentage of emission into one particular waveguiding mode of interest. For example,

typical semiconductor waveguide core materials for use in practicing the invention have a refractive index n_{core} greater than about 2.5, such as from about 3 to about 3.5 and above for InGaAsP, AlGaAs, etc. materials, whereas typical low-refractive index mediums for use in practicing the invention have refractive index n_{low} below about 2.0, such as from about 1.6 to about 1.0 for silica, silicon nitride, acrylic, polyimide, aluminum oxide, epoxy, photoresist, PMMA, spin-on glass, polymers with low absorption at the emission wavelength, or air. The ratio of the refractive indices $n_{\text{core}}/n_{\text{low}}$ has to be larger than about 1.3 to obtain substantial advantages of the invention.

The waveguide core comprises an active medium having major and minor sides and semiconductor guiding layers proximate the major sides to define a generally rectangular core cross-section comprising a width dimension and thickness dimension. The width dimension or direction is parallel to the substrate on which the waveguide is disposed, while the thickness dimension or direction is perpendicular to the substrate.

The strong photon confinement is provided in the width direction and the thickness direction in one embodiment. Low refractive index materials described above are the materials residing on all sides of the waveguide core along the width direction and thickness direction.

Optical coupling of the device described hereabove to an output can be effected by an

output-coupled waveguide proximate a portion of the periphery of the waveguide core in a manner to achieve resonant photon tunneling. A typical design can consist of a cavity coupled to a U-shaped output-coupled waveguide encircling part of the cavity with a small low-refractive-index gap between the output-coupled waveguide and the photonic-wire waveguide of the cavity. In order to achieve resonant photon tunneling of photons, the mode width for the electromagnetic field mode propagating in the output-coupled waveguide must be close to the mode width for the electromagnetic field mode propagating in the cavity. This will ensure that the field modes propagating in the output-coupled waveguide and the cavity have similar propagating velocities so that they can couple to each other with maximal efficiency.

The vertical layer structure of the output-coupled waveguide can be the same as that of the photonic-wire waveguide that forms the cavity. In that case, the output waveguide is excited by optical or electrical pumping to avoid absorption of light by the unexcited active layer(s) in the waveguide. To avoid the need for pumping the output-coupled waveguide, its vertical structure may be the same as that of the cavity's photonic-wire waveguide but without the active medium. The output-coupled waveguide can be formed at a level on a substrate compatible with an integrated optical circuit present on the substrate so as to provide light output signals to the optical circuit.

5 A typical single light emitting device as opposed to integrated circuit device) useful for practical applications can be provided via cleaving the ends of the U-shaped waveguide. The cleaved ends will provide radiation of the light in the output-coupled waveguide into free space (i.e. air). The spatial mode profile of this free-space radiation can be manipulated as described below.

10 The above objects and advantages of the present invention will become more readily apparent from the following detailed description taken with the following drawings.

15 DESCRIPTION OF THE DRAWINGS

Figure 1 is a perspective view of a ring-shaped photonic-wire light emitting device in accordance with one embodiment of the invention with an arcuate output-coupled waveguide encircling a portion of the periphery of the photonic-wire waveguide.

20 Figure 2, 2-1 and 2A are a partial cross-sectional view through the cavity formed with an annular-shaped waveguide of the light emitting device of the invention.

25 Figures 3, 4, 5, and 6 are schematic views of variations of closed loop waveguides.

Figure 7 is a schematic view of a cavity formed with a circular, annular-shape photonic-wire waveguide with roughened side walls.

30 Figure 7A is a view illustrating electric field mode relative to radius of curvature of

Figure 7. In Figure 7A, d_1 is mode width of mode 0, d_2 is mode width of mode 1, d_1 is waveguide width wherein $d_1 = R_{1out} - R_{1in}$ and d_1 is greater than d_2 and about equal to d_2 .

5 Figure 8 is a schematic view of another cavity formed with a closed-loop photonic-wire waveguide with roughened side walls.

10 Figure 9 is a schematic view of a photonic-wire light emitting device and a U-shaped output-coupled waveguide, optical lens and optical fiber pursuant to an embodiment of the invention.

Figure 9A is a perspective view of a portion of Figure 9.

15 Figure 10 is a perspective view of a photonic-wire waveguide of still another embodiment of the invention illustrating local electrical pumping thereof by current i_c . Figure 10A is a partial cross-sectional view at a location through the waveguide of Figure 10 at the encircled region. Figure 10B is a partial cross-sectional view at another location through the waveguide of Figure 10 at the encircled region showing a p-n junction for electrical pumping.

20 Figure 11 is a perspective view of an electrically pumped photonic-wire waveguide (current i_c) and output-coupled waveguide (current i_c') of yet another embodiment of the invention. Figure 11A is a partial cross-sectional view at a location through the waveguide of Figure 11 at the encircled region.

30 Figure 12 is a perspective view of an electrically pumped photonic-wire waveguide of

still another embodiment of the invention. Figure 12A is a partial cross-sectional view at a location through the output-coupled waveguide of Figure 12 at the encircled region. Figure 12B is a partial cross-sectional view at a location through the photonic-wire waveguide of Figure 12 at the encircled region.

Figure 13 is a perspective view of an electrically pumped photonic-wire waveguide of yet an additional embodiment of the invention illustrating local electrical pumping of the output-coupled waveguide (current i_c'). Figure 13A is a partial cross-sectional view at a location through the waveguide of Figure 13 at the encircled region.

Figure 14 and 15 are schematic views of a photonic-wire waveguide coupled to a plurality of output-coupled waveguides pursuant to still another embodiment of the invention.

Figure 16 is a graph of intensity versus wavelength. Figure 16A is lasing power versus peak pump power.

DETAILED DESCRIPTION OF THE INVENTION

Referring to Figures 1 and 2, a photonic-wire light emitting device 10 in accordance with one embodiment of the invention is illustrated schematically as including a relatively high refractive index photonic-wire waveguide core 20 which is surrounded by relatively low refractive index medium 23 in a width direction of the core 20 and relatively low refractive medium 33, 35 in

a thickness direction of the core 20. In particular, the high refractive index semiconductor waveguide core 20 is surrounded on lateral sides 20a, 20b by relatively low refractive index medium 23 on two sides 20a, 20b defining the width dimension d_s of the waveguide core by the relatively low refractive index medium. The waveguide core 20 also is surrounded on the top and bottom sides 20c, 20d by relatively low refractive index medium 33, 35 on top and bottom sides defining the thickness dimension d_w of the waveguide core 20 by the relatively low refractive index medium 33, 35. The surrounding of the waveguide core 20 in both these dimensions or directions is effective such that photons are tightly confined in all directions perpendicular to their direction of propagation. The strong confinement forms strong confining potential walls for photons and restricts photons to move relatively freely only in one direction, and the waveguide is called a photonic-wire waveguide. The strong potential is necessary to affect the emission properties of the optically active, excitable medium of the waveguide, and can be used to dramatically increase the percentage of emission into one particular waveguiding mode of interest.

For example, typical semiconductor waveguide core materials for use in practicing the invention have a refractive index n_{core} greater than about 2.5, such as from about 3 to about 3.5 and above for InGaAsP, AlGaAs or InGaN materials, whereas

typical low refractive index mediums described below for use in practicing the invention have refractive index n_{low} below about 2.0, preferably below 1.6, such as from about 1.5 to about 1.0. The ratio of the refractive indices $n_{\text{core}}/n_{\text{low}}$ is larger than about 1.3 to obtain substantial advantages of the invention, and preferably larger than 2.0.

For purposes of illustration and not limitation, in Figures 1 and 2, the waveguide core 20 is disposed on top of the substrate 26, which may comprise InP (indium phosphide) or other suitable substrate material, such as GaAs (gallium arsenide). The relatively low refractive index medium 23 includes air (refractive index of 1) that borders the left and right sides 20a, 20b of the waveguide core 20 in Figure 1. The relatively low refractive index medium 23, 33, 35 includes air (refractive index of 1.0) in Figure 1. The low refractive index medium 23, 33, 35 serve to spatially confine photons tightly in the width and thickness directions perpendicular to photon circumferential propagation direction in the waveguide core. Other low refractive index medium that may be used include acrylic, epoxy, silicon dioxide (SiO_2), aluminum oxide, silicon nitride, spin-on glass, polymers with low absorption at the emission wavelength, photoresist, poly-methyl metacrorate, and polyimide. The same or different low refractive index mediums 23, 33, 35 can be used on the sides 20a, 20b, 20c, 20d.

The relatively high refractive index

photonic-wire waveguide core 20 comprises an optically active excitable medium (hereafter active medium) 30 which can give rise to radiation or absorption of electromagnetic field energy and, in particular, gain or luminescence, when pumped or excited optically or electrically. The active medium 30 typically comprises layers 31 of semiconductor quantum well, quantum wire, or quantum dot (layers shown in Figure 2-1) having major sides 31A parallel to one another and minor sides that are defined by the thickness of each layer. In order to more effectively radiate into the guided mode, the active medium is located generally around the midpoint of the core thickness dimension dw and each may comprise $In_{0.53}Ga_{0.47}As$ or other suitable active quantum well, quantum wire, or quantum dot material (see Figure 2A).

Disposed proximate the major sides of the active medium are major sides of guiding semiconductor layers such as layers 32a, 32b which also have minor sides defined by the thickness of the layers involved. As shown in Figure 2, barrier layers 31B (two shown) are disposed between the quantum well layers 31. The guiding or barrier layers each may comprise $In_{0.84}Ga_{0.16}As_{0.67}P_{0.33}$ or other suitable passive guiding or barrier material (see Figure 2A). The refractive index of the guiding layers 32a, 32b and active medium 30 is at least 1.3 times as great as that of relatively low refractive index medium 23, 33, 35 bordering the sides 20a, 20b, 20c, 20d of the

waveguide core.

5 The active medium 30 alternately may comprise one or more optically active rare earth ion containing layers in lieu of the quantum well layers 31. The rare earth ion containing layers are located generally at the midpoint of the core thickness dimension dw and each can comprise rare earth ion doped semiconductor material (e.g. Er^{+3} doped InP) or other suitable optically active
10 rare earth ion containing material. When the rare earth ion containing layers are employed, the guiding layers comprise the same material described above.

15 In practicing embodiments of the invention, the photonic-wire wave-guide can comprise semiconductor materials $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$ or $\text{In}_x\text{Al}_{1-x}\text{Ga}_y\text{As}$ as the n_{core} material and an aforementioned material with a refractive index of about 1.6 or lower as the n_{low} material. Alternatively, the photonic-wire
20 waveguide can comprise semiconductor materials $\text{In}_x\text{Ga}_{1-x}\text{N}$ or $\text{Al}_x\text{Ga}_{1-x}\text{N}$ as the n_{core} and n_{high} materials and a material with a refractive index of about 1.6 or lower as the n_{low} material. Still further, the photonic-well waveguide can comprise semiconductor
25 materials $\text{Al}_x\text{Ga}_{1-x}\text{As}$ or $\text{In}_x\text{Ga}_{1-x}\text{P}$ as the n_{core} and n_{high} materials and a material with a refractive index of about 1.6 or lower as the n_{low} material.

30 The active medium 30 can be excited by suitable means such as optically (e.g. by a pumping laser providing pulsed light of appropriate duty cycle) or electrically (e.g. by electrical current pulses of appropriate duty

cycle comprising injection current pumping through a p-n diode junction) as is known. Injection current is supplied to core 20 via conventional transparent conductor (not shown) such as indium tin oxide at suitable location in the waveguide structure.

The layers 31, 32 define in Figure 1 a circular shape waveguide core 20 having an inner diametral rim or surface and outer diametral rim or surface. When the circular shape is closed onto itself as such, forming a closed loop, a high Q and high gain cavity is provided. Let the length of this cavity be L_c , defined approximately by the averaged physical length of the outer and inner perimeters of the closed loop. The normalized cavity length is then defined by $L_c = L_c / (\lambda / n_e)$, where λ is the emission wavelength of the active layers and n_e is the effective refractive index for the electromagnetic field mode propagating in the waveguide core 20 (n_e typically is well approximated by the refractive index of the waveguide core material n_{core} but may fall to below n_{core} , such as about $0.7 n_{core}$ when the normalized thickness is thin, such as about 0.4). The normalized length of the cavity is typically smaller than 1000. The high Q (Q being quality value of the cavity at transparency or in the absence of material absorption) cavity can be an efficient laser cavity and in particular, can be a lasing microcavity. The invention is not limited to circular shaped waveguide cores and can be practiced with linear shaped waveguide cores

and waveguide cores having arcuate segments and linear segments.

For efficient operation of the light emitting device or laser, it is desirable to capture as much emission power into the electromagnetic field mode of interest (usually a guided TE mode or TM mode of the waveguide) both spatially and spectrally. The spatial mode is usually defined by the spatial profile of the guided mode. The spectral modes are clearly defined in a cavity situation for which there are discrete cavity resonance frequency modes. The spectral modes are then the cavity resonance frequency modes.

The percentage of emission captured spatially into the electromagnetic field mode of interest will be denoted by $\text{Beta}(\text{space})$. The emission from an optically active medium usually spans a certain frequency range given by an effective spectral width, d_{fe} . For those emission that is captured spatially into the field mode of interest, there are many cavity resonance frequency modes it can emit into, the percentage of which captured into the resonance frequency mode of interest being denoted by $\text{Beta}(\text{Freq})$. Let the frequency spacing between two adjacent resonance frequency modes be given by d_{fc} . For the case where the spectral width of the emission is larger than d_{fc} (i.e. d_{fe} greater than d_{fc}), the value of $\text{Beta}(\text{Freq})$ is approximately given by $\text{Beta}(\text{Freq}) = (d_{fc}/d_{fe}) * (2/\pi)$. For high $\text{Beta}(\text{Freq})$ value, it is generally desirable to have narrow emission spectral width, such as that typically provided by

semiconductor quantum wells, quantum wires, quantum dots, or rare earth ions.

5 The total percentage of emission captured into the desired field mode both spatially and spectrally is the product of Beta(space) and Beta(Freq) and is denoted by Beta(tot). That is Beta(tot) = Beta(space)*Beta (Freq). Beta(tot) is called the spontaneous emission coupling efficiency.

10 The value of dfc is related to the cavity length via a simple relation of $dfc = c/(n_e L_c)$, where c is the speed of light in vacuum (10^8 meters per second), L_c is the round trip physical length of the cavity, and n_e is the effective propagation refractive index for modes propagating in the
15 cavity (or more accurately $n_e L_c$ is the effective round trip optical path length of the cavity). An optical cavity can be said to be an ideal microcavity when the cavity size L_c is so small as
20 to give a large dfc value so that Beta(Freq) approaches unity (i.e. when dfc is almost as large as dfe so that Beta(freq) = 1.0). In practice, an optical cavity can be said to be a microcavity if
25 it's Beta(freq) is larger than approximately 0.03 (10 times larger than that of the conventional semiconductor laser structure described). It can be said to be a good microcavity if Beta (Freq) is larger than 0.1.

30 The present invention provides in an embodiment a light emitting device having Beta(tot) much larger than that available from the usual semiconductor laser cavity design and from

which a working device can be realized. For example, a typical prior semiconductor laser cavity design with a 300 micron long linear cavity defined by a ridge waveguide exhibiting a
5 Beta(tot) value of about 0.00001 for a Beta(space) = 0.004 and Beta(Freq) = 0.003. The present invention provides a light emitting device having a Beta(tot) which can be as large as 0.3 and higher achieved through combined use of photonic-
10 wire waveguides, microcavity structure and an appropriate active medium, such as quantum wells.

A particular photonic-wire light emitting device in accordance with an embodiment of the present invention comprises a relatively high refractive index photonic-wire semiconductor
15 waveguide core 20. The photonic-wire waveguide core is formed into an arcuate shape, linear shape, and combinations thereof. As described in more detail below, when the photonic-wire
20 waveguide 12 is closed onto itself forming a close loop cavity, a high Q and high gain cavity is provided. The details of the cavity design are essential for achieving high Q value and will be described below. The high Q cavity can be an
25 efficient cavity for the light-emitting device or laser in particular, can be a lasing microcavity.

The high refractive index semiconductor waveguide core is surrounded by relatively low refractive index medium on all sides 20a, 20b,
30 20c, 20d. This confines photons tightly in all directions perpendicular to their direction of propagation. The strong confinement forms strong

confining potential walls for photons and restricts the photons to move relatively freely only in one direction, and the waveguide is called a photonic-wire waveguide. The strong potential is necessary to affect the emission properties of the optically active layers of the waveguide core, and can be used to drastically increase the percentage of emission into one particular waveguiding mode of interest. For example, typical semiconductor waveguide core materials for use in practicing the invention have a refractive index n_{core} greater than about 2.5, such as from about 3 to about 3.5 and above for InGaAsP or AlGaAs materials, whereas typical low-refractive index media for use in practicing the invention have refractive index n_{low} below or about 2.0, such as from about 1.6 to about 1.0 for silica or air. The ratio of the refractive indices $n_{\text{core}}/n_{\text{low}}$ has to be larger than about 1.3 to obtain substantial advantages of the invention.

The waveguide core 20 comprises an active medium 30 having major and minor sides and semiconductor guiding layers proximate the major sides to define a generally rectangular core cross-section comprising a width dimension d_s and thickness dimension d_w . The width dimension or direction is parallel to the substrate on which the waveguide is disposed, while the thickness dimension or direction is perpendicular to the substrate.

The strong photons confinement is provided in the width and thickness directions. The low

refractive index materials described above are the materials residing on all sides 20a, 20b, 20c, 20d of the waveguide core 20 along the width and thickness direction. A normalized width ds_n , greater than 0.6 and not exceeding 1.1 and a normalized thickness dw_n , greater than 0.1 and not exceeding 0.5 will provide optimal emission efficiency into the lowest-order guided mode, giving a Beta(space) of about 0.25 or larger. However, a normalized width of typically 1.0 and up to 4.0 and a normalized thickness of typically 0.1 up to 0.6 will still provide reasonable efficiency. A normalized thickness exceeding 0.5 and up to 1.1 and a normalized width of larger than 0.5 and less than 4.0 will still provide device of interest, although it will generally be operating with multiple waveguide modes, and will have relatively low emission into the lowest-order mode. This requirement may be relaxed to have normalized wavelength width larger than 4.0 in the case where the waveguide is in the form of a circular arc with a large curvature as described in detail below. The normalized width dimension ds_n for the strong confinement direction is expressed as $ds_n = ds/ds_{\lambda}$ with $ds_{\lambda} = \text{Lambda}/n_{\text{eff}}^3$, where Lambda is the active-medium emission wavelength in free space (i.e. vacuum or in the absence of material medium) and n_{eff}^3 is the effective refractive index given by $n_{\text{eff}}^3 = \text{Sqrt}(n_{\text{core}}^2 - n_{\text{low}}^2)$, where n_{core} is the refractive index of the waveguide core, n_{low} is the refractive index of the materials surrounding the waveguide core, and Sqrt

denotes square rooting. The normalized thickness dimension dw_s for this weak confinement direction is expressed as $dw_s = dw/dw_{\text{lambda}}$ with $dw_{\text{lambda}} = \text{Lambda}/n_{\text{eff}}^w$, where Lambda is the active-layer emission wavelength in free space (i.e. vacuum or in the absence of material medium) and n_{eff}^w is the effective refractive index given by $n_{\text{eff}}^w = \text{Sqrt}(n_{\text{core}}^2 - n_{\text{low}}^2)$.

In a particular embodiment, the normalized width of the photonic-wire waveguide ds_s is about 0.85 and the normalized thickness dw_s is about 0.4 with the index ratio $n_{\text{core}}/n_{\text{low}}$ larger than 2.0.

In the limit of small enough photonic-wire waveguide core dimensions, the strong confinement of photons in the photonic-wire waveguide core will give rise to a drastic modification of the photonic density of states (quantum states for which the photons are allowed to be emitted into) in such waveguide. This drastic modification of the photonic density of states will cut off certain dipole emission from the active medium and relatively enhances emission from one particular dipole orientation, specifically, when the active medium is excited, the emission from the active medium can modeled as radiation from three types of mutually orthogonal electric dipoles; namely, one type of dipole pointing in the thickness direction called the vertical dipole, one type of dipole pointing in the width direction called the horizontal dipole, and one type of dipole pointing along the axis of the waveguide (or direction of photon propagation of the guided mode) called the

axial dipole. In addition to having emission from three types of dipoles (vertical, horizontal, and axial dipoles), the emission energy from each type of dipole can go either into the TE (transverse electric) polarization or the TM (transverse magnetic) polarization of the guided modes.

Normally only one of the dipole types contributes most of the energy into the guided modes of interest and the emission power from the other two dipole types is almost fully wasted. If the unused emission power from these other two dipole types can be strongly reduced, then one can save the pumping power supplied to the active medium by a factor of 60% or larger.

As part of the invention, we have found that with use of photonic-wire structure, we can substantially reduce or eliminate some of these unwanted dipole emissions, leading to a great increase in efficiency.

Via the use of photonic-wire waveguide, if the normalized width dimension ds_n is larger than about 0.6 and smaller than about 0.85 (or up to about 1.1) and if the normalized thickness dimension dw_n is larger than about 0.1 and smaller than about 0.5, the emission power from the vertical dipole and axial dipole can be strongly reduced. This means that most of the pumping power supplied to active medium will end up as emission power from the horizontal dipole. Furthermore, most of the power from the horizontal dipole will go to excite mainly the TE polarization modes in the waveguide. Moreover,

with the chosen dimensions of ds_n and dw_n , the waveguide can only support the lowest order guided mode, and the strong confinement in the waveguide ensures that the horizontal dipole will not radiate much to the radiation modes that escape the waveguide. Combining the aforementioned effects means that most of the emission power from the active medium will go into only one single waveguide mode, namely the lowest-order guided mode with TE polarization.

Hence, through a combination of quantum effect which strongly reduces unwanted emission from the two dipole types, and strong photon confinement which allows the emission from the remaining horizontal dipole to couple only into the guided mode and not the radiation modes that escape the waveguide, it is possible to get huge percentage of the emission power into a single TE polarized mode of interest.

This can lead to an extremely large spatial spontaneous emission factor $\text{Beta}(\text{space})$ of larger than 0.30. The theoretical maximal value of $\text{Beta}(\text{space})$ is 0.5 due to the existence of two opposite directions of propagation for the waveguide modes (i.e. at most only half the emitted power can go into one of the propagating mode directions). Hence the $\text{Beta}(\text{space})$ value for the photonic-wire waveguide is close to the ideal value of 0.5. This is much larger than the $\text{Beta}(\text{space})$ value of a typical conventional ridge waveguide used in a typical light emitting device, for which $\text{Beta}(\text{space})$ is about 0.004.

5 The extremely large Beta(space) value leads
 to a significantly enhanced optical gain for the
 active medium and efficiency for the conversion of
 the pumping power, which makes it possible to
 10 achieve lasing with a small cavity. In this
 invention, we have realized such a photonic laser
 and show that lasing can be achieved in a
 microcavity with an extremely small cavity volume
 of less than 0.3 cubic micrometers or 10^{-18} cubic
 15 meters, which is about the smallest cavity ever
 made to lase. We also show that in a particular
 realization the pumping threshold needed for
 lasing in such a small cavity can be as low as 100
 microWatts, which is about 100 times lower than
 20 the threshold pumping power for a typical 300
 micron long semiconductor laser.

When the dimensions of the photonic-wire
 waveguide are larger than the above prescribed
 dimensions, the spontaneous emission coupling
 25 efficiency into the lowest-order spatial mode of
 opportunity is approximately:

$$\text{Beta(space)} = \frac{\cos^{-1}(1-1/rs) * \cos^{-1}(1/rw)}{(3\pi^2 * fw * fs)}$$
 where $fw = dw_n$ if dw_n is greater than
 $1/\text{Sqrt}(3) = 0.577$ and $fw = 1$ if dw_n less than
 30 $1/\text{Sqrt}(3)$, and $fs = ds_n$ if ds_n is greater than
 $1/\text{Sqrt}(3)$ and $fs = 1$ if ds_n less than $1/\text{Sqrt}(3)$
 where Sqrt is square root and where \cos^{-1} is the
 inverse cosine or arc-cosine and $rs = n_{\text{core}}/n_{\text{low}}$ and
 $rw = n_{\text{core}}/n_{\text{high}}$. The Beta(space) defined is a
 35 function of emission captured spatially into one
 particular polarization (TE and TM) of the lowest-
 order guided mode that is propagating in a

particular direction of propagation of the waveguide (these are two mutually opposite directions for which a wave can propagate in the wave guide). The above formula gives a good estimation of Beta(space) generally except in structures where ds_n is less than 0.5 or dw_n is less than 0.6. When ds_n is less than 0.5, for example, emission into one of the two polarizations may be cutoff, leading to a factor of 2 increase in the Beta(space) factor for the remaining polarization. When dw_n and ds_n are both less than 0.1, emission may be reduced or cutoff, leading to a drastic decrease in the Beta(space) value. A more exact value for Beta(space) can be calculated based on quantum electrodynamic calculation which can deviate (typically larger) from this simple estimation by a few times especially for the case where ds_n or dw_n is less than 0.5.

This Beta(space) value of up to about 0.3 and higher attributed to the photonic-wire waveguide core in accordance with the present invention is substantially larger than that of the typical semiconductor laser waveguide structure with Beta(space) = 0.004.

Moreover, this large Beta(space) value coupled with the high Q value micro-cavity design for which Beta(Freq) is close to 1, provides Beta(tot) up to about 0.03 for the waveguide core in accordance with the present invention, which is much larger than the Beta(tot) factor of typical semiconductor laser waveguide structure with

Beta(tot) = 0.00001. The Beta(tot) will still be as large as 0.0035 (350 times larger than that of the typical semiconductor laser structure) even when the cavity is not at the ideal microcavity limit but is reasonably "micro" so that Beta(Freq) is greater than 0.05.

A reasonable microcavity with Beta(Freq) greater than 0.05 can be achieved by closing the photonic-wire waveguide 12 on itself to form a small closed loop cavity. Let the cavity's physical length be denoted by L_c and the effective propagating refractive index for mode in the cavity be denoted by n_e (n_e is closely approximated by n_{core} except when ds is small so that ds_e is less than 1.0 at which n_e can fall substantially below n_{core}). The normalized cavity length is defined by $L_{cn} = L_c / (\lambda / n_e)$. A normalized cavity length of typically 300 or smaller is needed to achieve Beta(Freq) of about 0.05 and larger (assuming the emission width of the optically active medium is about 10^{13} Hertz (or 70 nanometers), which is typical for that of a quantum well emitting at 1.5 microns, $L_{cn} = 300$, and $n_e = 2.4$ (for $ds_e = 0.3$), gives $d_{fe} = 10^{13}$ Hertz, $d_{fc} = 1.7 \times 10^{12}$ Hertz, and Beta(Freq) = 0.05.

Generally, the microcavity with cavity L_c specified above provides a Beta(Freq) of about 0.05 and larger when the emission frequency width from the active medium is equal to about 1/20 of the optical emission frequency exhibited by semiconductor quantum wells.

One particular embodiment of the invention

with near optimal properties for operation at 1.1 micron to 1.6 micron wavelength range employ dimensions d_s that is about 0.6 micron or smaller and dimension d_w that is 0.3 micron and smaller with d_s being larger than about 0.2 micron and d_w being larger than about 0.03 micron.

Another particular embodiment of the invention for operation at 0.2 micron to 0.7 micron wavelength range employs a dimension d_s that is about 0.3 micron or smaller and dimension d_w that is about 0.3 micron and smaller with d_s being larger than about 0.04 micron and d_w being larger than about 0.01 micron.

Still a further particular embodiment of the invention for operation at 0.6 micron to 1.0 micron wavelength range employs a dimension d_s that is about 0.4 micron or smaller and dimension d_w that is about 0.2 micron and smaller with d_s being larger than about 0.1 micron and d_w being larger than about 0.02 micron.

The general design for such high-Q cavity is illustrated in Figure 3, which schematically shows a cavity formed by a closed loop of photonic-wire waveguide 12 with one or more arcuate shapes or one or more linear shapes, or combinations thereof. Each arcuate segment can be formed by one or more circular segments or some times by many linear segments of sufficiently short lengths joined to each other with a small bend. The simplest design involves no linear section and is in the form of a perfect circle as shown in Figure 4. A more complicated variation consisting of an

arcuate segment and a linear segment is shown in Figure 5, while a variation consisting of two arcuate segments and two linear segments are shown in Figure 6.

5 In order to achieve low loss and hence high Q for the cavity, the curvature of the arcuate segments cannot be arbitrary but must satisfy a minimal radius of curvature. In addition, two adjacent segments joined to each other must have
10 the same tangents for their line sections at the joint. For the sake of defining the radii of curvature of the arcuate segments, each arcuate segment will be approximated by one or more circular segments. High accuracy of approximation
15 is achieved when the error of approximation involves spatial deviations smaller than one tenth the optical wavelength of emission in the photonic-wire waveguide. The outer rim of each such circular segment is formed by a circular arc
20 drawn with a certain radius of curvature R from a certain center C. We can label the Rs and Cs of all such circular segments in Figure 3 by R1, R2 etc. and C1, C2, etc., respectively, which will be referred to as their radii and centers of
25 curvature.

 If the center of curvature R_i ($i = 1, 2, \text{etc.}$) for arc i is too small, photons in the photonic-wire waveguide can escape from the waveguide and radiate in the direction away from the center of
30 curvature. This will result in cavity photon loss and hence low cavity Q value. To avoid loss, the design requires that:

$$|R_i| > -[\lambda/2\pi] * \ln[\lambda/2\pi n_{core} L_{arc}] / \ln[n_{core}/n_{low}]$$

where L_{arc} is the length of the circular arc and \ln is the Natural Logarithm. For the purpose of illustration, it is necessary to specify if the curved arc is around the center designated P_c or away from the center. If it is around the center, R_i is assigned a positive sign and if it is away from the center, R_i is assigned a negative sign.

More specifically, let point P_c be a point in the center region of the closed loop, we will assign R_i ($i = 1, 2$, etc) for arc i to be positive if its center of curvature C_i lies on the same side of arc i as point P_c , and negative (i.e. $R_i = -|R_i|$) if its center lies on opposite side of the arc i as point P_c . For the general case in Figure 3, R_i can either be positive or negative (e.g. R_2 is negative).

Lasing threshold is achieved when the round trip optical gain of the electromagnetic field mode propagating in the cavity due to the excited active layer exceeds the round trip optical loss. The round trip loss can be due to absorption and scattering by impurities or defects in the waveguides, as well as roughness on the waveguide side walls. It can also be due to photons leaking out to the output-coupled waveguide described below.

The pumping power needed to achieve lasing threshold is partially used to cause inversion in the active layer at which the active medium will become transparent and begin to contribute to

optical gain. This is called the transparency pumping power. It is partially used to achieve additional gain above the transparency point so as to overcome the cavity loss as described above.

5 This is called the additional-gain pumping power. Due to the high Q, low loss nature of the cavity, the additional-gain pumping power may be a small part of the total threshold pumping power. In that case, most of the threshold pumping power is

10 used to make the medium transparent (i.e. used as transparency pumping power). The transparency pumping power needed is proportional to the total material volume of the active medium. It can be reduced by using thinner active medium or by

15 reducing the area of the active medium in the cavity. Hence, the threshold pumping power may be reduced by having the active medium present only along a small section of the entire length of the waveguide that forms the cavity (this is

20 illustrated in Figures 10, 10A, 10B where a small section 40 of the waveguide has a photonic-wire structure 42 with an active medium 45, while the remaining length of the waveguide 50 that forms the cavity (40 and 50) has a photonic-wire

25 waveguide structure 52 sans an active medium.

To reduce side-wall scattering loss, it is in general desirable that the side walls of the photonic-wire waveguide core, especially the two

30 side walls 20a, 20b for the strong photon confinement in the width direction, be fabricated with smooth surfaces having roughness less than one tenth of λ/n_{core} . Power loss due to side-

wall scattering loss is also dependent on the refractive index difference between the waveguide core and the surrounding materials, or specifically directly proportional to $(n_{\text{core}}^2 - n_{\text{low}}^2)^2$.

5 Thus, reducing the refractive index difference between the waveguide core and the surrounding materials can reduce the scattering loss. However, as described above, it will trade-off (i.e. reduce) the efficiency of emission given
10 by Beta(Freq), which is also dependent on the refractive index difference. These considerations must be taken into account in the design and fabrication of the cavity.

15 The requirement of smooth waveguide side walls, however, can be relaxed for those highly curved arcuate segments where the R_i 's are small. In that situation, as explained below, it may actually be desirable to have roughness fabricated on some of the side walls to enforce lasing in the
20 lowest-order guided mode.

 The situation is illustrated for the simplest case of a circular, annular core cavity in Figure 7. When the radius of curvature R_1 in Figure 7 is smaller than approximately 50 times the optical
25 wavelength in the waveguide core 20 (i.e. R_1 less than $50 \lambda / n_{\text{core}}$), the strong curvature can cause the guided modes to squeeze towards the outer rim of the waveguide core as shown by the guided mode cross-section in Figure 7A. The outer
30 or inner rim of a curved segment is the side wall (20a or 20b) of the photonic-well waveguide that is respectively closer to or farther from the

segment's center of curvature. Generally, the large curvatures squeeze the mode width of the lowest-order mode to less than about ten optical wavelengths in the photonic-wire waveguide, and force it to propagate along the outer rim of the curved waveguide. In particular, the lowest-order mode (mode 1) is squeezed to a mode width d_1' of less than $10 \lambda / n_{\text{core}}$. If the waveguide width d_s is larger than the mode width d_1' , the lowest-order mode will touch mainly the outer rim of the curved waveguide due to centrifugal force on the photons undergoing curvilinear propagation. The higher-order modes, such as the second-order mode 2, will have a mode width d_2' larger than d_1' and will touch more of the inner rim of the curved waveguide. As a result, roughness along the inner rim of the waveguide will cause much more loss to the higher-order modes than the lowest-order modes, and will eliminate lasing in the higher-order modes when sufficient loss is imposed.

The waveguide width d_s typically is larger than the lowest-order mode of propagation and at least a portion of an inner rim of the closed loop is roughened to increase scattering loss on higher-order modes.

The general case is shown in Figure 8 for which there are multiple arcuate segments forming a closed loop cavity. In order for this configuration to work, it is desirable that every segment with substantial segment length has a radius of curvature R_i smaller than 50 times the optical wavelength in the waveguide core (i.e. R_i

less than $50 \lambda / n_{\text{core}}$). Straight segments can be viewed as curved segments with an infinite radius of curvature and are not desirable to be present in this scheme. The waveguide width d_s must be larger than the mode-width d_1' . A typical design has its normalized waveguide width d_{s_n} to be larger than 0.1 but smaller than approximately 10.0. For each segment, roughness can be present on the rim closer to its center of curvature. To eliminate lasing in the higher-order modes, roughness present on some portions of segment length may be sufficient (i.e. not the entire length must have roughness present on such side walls).

Note that since the lowest-order mode is squeezed to the outer rim and to a normalized mode-width of less than 10.0, the position of the inner rim would have no significant affect on its mode width if distance between the outer rim and inner rim is larger than the mode width d_1' . In fact, in that case, the clear presence of the inner rim is not needed and the waveguide region beyond a distance of about d_1' away from the outer rim can take on different physical forms such as different thicknesses or sidewall roughness without affecting the mode confinement or performance of the device.

Hence, the waveguide normalized width d_{s_n} can be 10.0 or larger without affecting the waveguiding or gain of the lowest-order mode significantly from the case where $d_{s_n} = 10.0$. Thus, in this situation we can relax d_{s_n} to have a

large value limited only by the allowed diameter of the cavity size such as 100, at which the curved waveguide will have a radius of curvature of $50 \lambda / n_{\text{core}}$. Thus, ds_c can be larger than 0.1 and less than 100. In practice, as the lowest-order mode only occupies a small region close to the outer rim, it is economical to keep ds_c to be around 4.0 or smaller such as to reduce the area of the active medium which can draw additional pumping power.

Optical coupling of the device described hereabove to an output can be effected by a light output-coupled waveguide W proximate a portion of the periphery of the waveguide core 20 in a manner to achieve resonant photon tunneling. The waveguide W is spaced by a small gap of low refractive index material (e.g. air) from the photonic-wire waveguide 12. The coupling involves a short section of the cavity and the waveguide W in which the photons in the cavity are propagating in parallel to each other. The refractive index of the gap region is lower than the refractive indices of the waveguide material and cavity material. The gap size typically is smaller than 10 and larger than 0.02 optical wavelength in the photonic-wire waveguide. The amount of coupling or energy transfer between the output-coupled waveguide W and the waveguide core 20 increases with decreasing gap size or increasing coupling length, where the coupling length is the length for which the output-coupled waveguide W proximates the waveguide core 20.

5 The vertical structure in the thickness
dimension of the output-coupled waveguide W can be
the same as that of the laser cavity. In that
case, it has to be excited by optical or
10 electrical pumping to avoid absorption of light by
the unexcited active medium in the waveguide as
illustrated in Figure 11. To avoid the need for
pumping the output-coupled waveguide W, its
vertical structure may be the same as that of the
15 laser cavity but without the active materials as
illustrated in Figure 12, 12A, 12B. The output-
coupled waveguide can be formed at a level on a
substrate 26 compatible with an integrated optical
circuit IC present on the substrate so as to
provide light output signals to the optical
circuit.

 The output-coupled waveguide W can also have
active materials present only along certain
sections of the waveguide as illustrated by
20 sections 55 and 56 of Figure 13. The sections 55,
56 with active materials can be pumped to achieve
population inversion, giving rise to optical gain
for light propagating in the waveguide W. This
can be used to provide further amplification of
25 optical power from the cavity, Figure 13A, leading
to a higher net optical power in the waveguide.

 If the active medium section is not pumped,
it can function as a detector in the following
manner. It can absorb light in the waveguide
30 which will cause population excitation of the
active medium in proportion to the light power
absorbed. The population excitation can be

detected for example via a closed electric circuit, leading to a circuit current. The circuit current is then an indication of the optical power in the waveguide. The active medium section can also function as a modulator by modulating the pumping power, leading to a modulation of optical absorption or gain of the active medium section and hence the optical power through the section.

The cavity may be coupled to one or more output-coupled waveguides W at different segments of the cavity as illustrated in Figure 14, providing six output ports 60, 61, 62, 63, 64, 65. It must be noted that light in the close loop cavity may be divided into two beams, one that propagates in the clockwise direction 70 and one that propagates in the counterclockwise direction 71. One or both of the beams may be brought above lasing threshold via external pumping.

The output-coupled waveguide W may also serve to couple light from other light source or another such photonic-wire light-emitting device, into the cavity, thereby forming input ports to the cavity. This is illustrated in Figure 15 where two input ports 70a, 71 and two output ports 72a, 73 to cavity 80 are shown.

The input ports are used to introduce light in the form of pulses or continuous wave beams into the cavity, which can affect the properties of light output from the cavity. In particular, the amplitudes, phases, frequencies, pulse duration, and polarization of the light output

from the output ports can depend on the amplitudes, phases, frequencies, pulse duration, and polarization of the light input into the input port. The dependence can be different depending
5 on the excitation level or population inversion of the active medium in the cavity, or on whether the input beams in the cavity are brought above or below the lasing thresholds.

This dependence comes about through the mechanisms of injection locking and light
10 transmission through a nonlinear optical cavity as is known for which light injected into a cavity can change properties of light in the cavity in terms of amplitudes, phases, frequencies, pulse
15 duration, and polarization, thereby leading to a change in the properties of the output light from the cavity. A change in the population excitation of the active medium in the cavity can lead to the change of cavity gain or loss, and the refractive
20 index in the cavity, thereby affecting the mechanism of injection locking or light transmission through a resonant cavity, which then affects the properties of the output light.

Such input-output dependence can be used for
25 processing signals or information coded in the properties of the input light beams, and can be a useful device for application to optical communications, optical interconnects, optical sensing, optical signal processing, and optical
30 computing.

The presence of both input and output ports allows two or more of the photonic-wire cavities

to connect to each other by connecting the output port(s) of one cavity to the input port(s) of the other cavity. This allows one to build up a circuit comprising one or more of such cavities, which by itself can be a high-density photonic-wire integrated circuit.

The properties (amplitudes, phases, frequencies, pulse duration, and polarization) of the output beams from the output ports can be changed (or modulated) by changing the excitation level of the active medium via modulating the pumping power supplied to excite the active medium, such as the external injection current i_c to the active medium when electrically pumped. Such modulation can be generally imposed at high rate or frequency if the $\text{Beta}(\text{tot})$ value of the cavity is high, especially when operating at above lasing threshold.

A typical single device useful for practical applications can consist of a laser cavity formed by waveguide 12 coupled to a U-shaped output-coupled waveguide W as shown in Figure 9. In order to achieve resonant photon tunneling of photons, the mode width for the electromagnetic field mode propagating in the output-coupled waveguide W must be close or similar to the mode width for the electromagnetic field mode propagating in the cavity. This will ensure that the field modes propagating in the output-coupled waveguide and the laser cavity have similar spatial width or propagating velocities so that they can couple to each other with maximal

efficiency.

By cleaving the ends WE of the U-shaped waveguide W shown in Figure 9, laser light radiation into free-space (i.e. air) can be obtained. The spatial mode profile in the width direction and thickness direction is determined by the width and thickness of the output-coupled waveguide, which can be changed at the ends via tapered waveguide sections shown, Figure 9A. Thus, the waveguide width dsg_{laser} and thickness dwg_{laser} at the laser is chosen to achieve maximal coupling of light, while the waveguide width dsg_{out} and thickness dwg_{out} at the end WE is chosen to achieve a certain spatial profile for the light output. In particular, the spatial mode profile of the free-space radiation mode in the width direction can be made to have the same size as the spatial mode profile in the thickness direction, thereby achieving a near circular output spot size. Circular output spot size is generally desirable to achieve efficient coupling into an optical fiber via use of the coupling lens as shown in Figure 9.

For purposes of illustration and not limitation, the photonic-wire light emitting device having the dimensions described above can be formed by a fabrication process involving nanofabrication techniques including electron-beam (e-beam) lithography and reactive ion etching (RIE). For example, an InP substrate can be coated with an epitaxial InGaAsP/InGaAs laser layer structure of 0.19 micron thickness. Within

the layer structure, three 100 Angstrom thick quantum well layers ($\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$) can be separated by 100 Angstrom thick guiding or barrier layers ($\text{In}_{0.84}\text{Ga}_{0.16}\text{As}_{0.33}\text{P}_{0.67}$). They can be sandwiched by two
5 700 Angstrom thick ($\text{In}_{0.84}\text{Ga}_{0.16}\text{As}_{0.33}\text{P}_{0.67}$) guiding or barrier layers on both sides.

A wafer bonding and etching technique can be used to transfer the thin waveguide core 20 on top of a low index SiO_2 cladding or medium or a GaAs substrate. First, 800 Angstrom thick SiO_2 is
10 deposited on a wafer via plasma enhanced chemical vapor deposition (PECVD). Electron-beam lithography is used to write the core pattern on PMMA (poly methyl methacrylate) coated on
15 top of the SiO_2 layer. The pattern then is transferred down to the SiO_2 layer by etching away the unmasked region using the RIE process with CHF_3 as the etchant gas under 31 millitorrs with 60 Watts plasma power and then the PMMA is removed.
20 The pattern in SiO_2 layer then forms the mask for subsequent etching of the InGaAsP layer. The RIE process is used to etch the structure down vertically through the 0.19 micron InGaAsP/InGaAs epitaxial layer structure into the InP substrate.
25 In this step, a gas mixture of methane, hydrogen, and argon can be used in a ratio of 10:34:10 under a gas pressure of 45 millitorrs and a plasma beam power of 90 watts plasma power.

In order to achieve to place the thin annular
30 waveguide core 20 on a low-refractive index material, the substrate is removed as follows. The RIE etched sample is deposited with 0.75

micron thick SiO_2 using PECVD. A piece of GaAs substrate covered with 0.75 micron thick SiO_2 deposited via PECVD is then prepared. The two substrates are SiO_2 face-to-face bonded together using acrylic. Finally, a highly selective HCl etchant (HCl plus H_3PO_4 in 1:1 ratio) was used to remove the InP substrate, leaving the photonic-wire light emitting structure on 1.5 micron thick SiO_2 on the GaAs substrate.

For purposes of further illustration and not limitation, photonic wire lasers were made as described above with an outer diameter of 4.5 microns and with a waveguide thickness of dw of 0.19 micron. These lasers were made with waveguide widths of ds of 0.25 micron and 0.4 micron. The photonic wire lasers so made were optically pumped with a 514 nanometer argon-ion laser modulated with 1% duty cycle in a vacuum-assisted Joule-Thomson refrigerator at 85 K. The beam was focused with a 40X microscope objective lens to a size larger than the size of the waveguide core. The scattered output was collected from the top of each waveguide core via the objective lens and dispersed by an optical grating spectrometer (resolution of 1 nanometer) and detected using a lock-in technique and a liquid-nitrogen cooled germanium detector.

Figure 16 shows the typical lasing spectra obtained from the photonic-wire laser of the invention with a waveguide with a width of 0.4 micron and thickness of 0.19 micron pumped by a 514 argon-ion laser modulated with 1% duty cycle

in a vacuum-assisted Joule-Thomson refrigerator at 85 K. Figure 16 indicates lasing at 1403 nanometers (nm). The dashed curve is the spectrum at around the lasing threshold where the peak pump power absorbed by the laser is approximately 95 microWatts. The lasing power as a function of the peak pump power is shown in the inset designated Figure 16A. Its spectral line width at 1.5 threshold was measured to be about 0.5 nm with a spectrum analyzer resolution of 0.1 nm. The cavity Q value was estimated to be $Q = 300$ from the emission line width of the enhanced photoluminescence below lasing threshold near the cavity resonance. This corresponds to a waveguide loss of 2% per roundtrip primarily due to the average surface corrugations of about 0.002 microns on the etched waveguide sidewalls.

The small area (cross-sectional area of 0.02 microns squared) of the photonic-wire laser provides a large, spontaneous emission coupling efficiency of about 35%. The mode volume of this laser was only 0.27 microns cubed, and the total material volume was only 1 micron cubed.

While Figure 16 indicates that the photonic-wire laser of waveguide width of 0.4 micron lased at 1403 nm, the photonic-wire laser having a waveguide width of 0.25 micron did not lase under the same excitation conditions described above. The lack of lasing was attributed to suppression of the emission into the lowest order guided mode when ds_0 is about 0.65 micron (actual ds of approximately 0.3 micron). The large drop in

emission into the lowest-order guided mode is attributed to a large plunge in the photon density of states as well as an increase in the mode area at the very small waveguide dimensions, although Applicants do not wish or intend to be bound by any theory in this regard. As the waveguide width dimension of 0.25 micron creates d_s approximately equal to d_w less than 0.65 micron, the laser structure will have a low gain, and hence cannot lase. These results indicate that photonic-wire lasers of the invention have a minimum waveguide cross-sectional area below which the Beta value can become small and lasing will cease. Thus, the photonic-wire lasers of the invention must have a waveguide cross-sectional area greater than this minimum value.

Although the active medium materials is shown in the form of layer with a width equal to the waveguide width, those skilled in the art will recognize that the specific shape and dimensions of the medium can vary and the gain provided by the medium is dependent mainly on its volume of occupation being primarily at the center region of the cross-section of the waveguide core.

Although the low refractive index materials 23 and low refractive index materials 30, 32 are described as having a particular refractive indices, those skilled in the art will recognize that they are used to indicate the typical refractive indices possessed by these materials. For example, with in each material, it is possible to have small refractive index fluctuations or

variations spatially without affecting the mode confinement in the waveguide core or the performance of the device.

5 Although the waveguide core 20 is shown with
a rectangular cross section, those skilled in the
art will recognize that the core shape can deviate
from a perfect rectangular shape with an averaged
thickness and width dimension of the invention and
as set in the appended claims with regard to mode
10 confinement and the performance of the device.

 Although the invention has been described
with respect to certain specific embodiments
thereof, those skilled in the art will recognize
that these embodiments are offered for purposes of
15 illustration rather than limitation and that the
invention is not limited thereto but rather only
as set forth in the appended claims.

CLAIMS

1. A light emitting device comprising a relatively high refractive index photonic-wire semiconductor waveguide core surrounded in all directions transverse to photon propagation direction by relatively low refractive index mediums to spatially confine photons strongly in said directions transverse to their propagation direction in the waveguide core, said waveguide core comprising an optically active excitable medium having major and minor sides and guiding semiconductor medium proximate said major sides, said active excitable medium and said guiding medium being so dimensioned in said transverse directions relative to the path of light propagation through the waveguide core as to provide greatly increased spontaneous-emission coupling efficiency for photons emitted into an electromagnetic field mode.

2. The device of claim 1 wherein the active excitable medium comprise quantum well layers, quantum wires, or quantum dots, and the guiding medium comprises layers.

3. The device of claim 1 wherein said semiconductor waveguide core comprises a refractive index of about 3 to about 3.5 and said relatively low refractive index medium comprises a refractive index of about 1.0 to about 1.6.

4. The device of claim 1 wherein the refractive index of the guiding layers is at least 1.3 times as great as that of relatively low refractive index medium materials bordering said sides of the waveguide core.

5. The device of claim 3 or 4 wherein the waveguide core has a generally rectangular cross-section with a width dimension and thickness dimension.

6. The device of claim 5 wherein the waveguide core includes a normalized width dimension greater than about 0.5 and less than about 4.0.

7. The device of claim 6 wherein the waveguide core includes a normalized thickness dimension greater than about 0.05 and less than about 1.1.

8. The device of claim 5 wherein the waveguide core includes an actual width dimension of about 0.025 micron to less than about 2.0 microns.

9. The device of claim 8 wherein the waveguide core includes an actual thickness dimension of about 0.025 microns to less than about 0.6 micron.

10. The device of claim 1 wherein the

photonic-well waveguide core forms a closed path for the photons propagating in the waveguide core with an optical path length of smaller than about 150 microns.

5

11. The device of claim 1 wherein the photonic-well waveguide core forms a closed path for the photons propagating in the waveguide core with a normalized optical path length of smaller than about 300.

10

12. The device of claim 1 wherein the photonic-well waveguide core forms primarily a circular cavity with a normalized optical path length of smaller than about 300.

15

13. The device of claim 1 which further comprises means for exciting said active medium above a lasing threshold.

20

14. The device of claim 10 wherein the waveguide core includes a normalized width of up to about 100 without affecting substantially the preferential single emission mode spatial profile due to confinement of the photons at an outer rim imposed by curvature of the waveguide core.

25

15. The device of claim 14 where optical coupling of said device to an output is effected by a light coupled waveguide proximate a portion of the periphery of the waveguide core in a manner to achieve resonant photon tunneling.

30

5 16. The device of claim 15 wherein the light output waveguide is formed at a level on a substrate compatible with an integrated optical circuit present on the substrate so as to provide light output signals to the optical circuit.

10 17. The device of claim 16 wherein the light output waveguide maintains a small gap size with the waveguide core of about 0.02 to less than 10 in units of optical wavelength in the waveguide.

15 18. The device of claim 16 wherein the light output waveguide maintains a small gap size with the waveguide core of about 0.01 to 5 microns.

20 19. The device of claim 15 wherein the active medium is present only along a small section of the optical path length to help reduce lasing threshold.

25 20. The device of claim 15 wherein the active medium is excited via injection current pumping.

30 21. The device of claim 16 wherein the active medium is excited via optical pumping.

 22. The device of claim 1 wherein the active medium comprises one or more quantum means.

 23. The device of claim 1 wherein the active medium comprises one or more rare earth ion

bearing layers.

24. The device of claim 1 having an annular waveguide core with an inner rim, said rim being
5 rough for R less than $50 \lambda / n_{\text{core}}$.

25. The device of claim 16 wherein the light output waveguide has a varied width and thickness.

10 26. The device of claim 1 coupled to an optical fiber.

27. Light-emitting device comprising at least one waveguide element providing for
15 spatially channeling a substantial fraction, characterized by $\text{Beta}(\text{space})$, of photons emitted from an excited medium into an electromagnetic field mode of interest using a photonic-wire waveguide as said waveguide element, and one
20 element for achieving a resonant optical cavity cooperating with said photonic-wire waveguide, the electromagnetic field mode of interest being a TE or TM guided mode of said photonic-wire waveguide, said photonic-wire waveguide comprising a
25 relatively high refractive index waveguide core with refractive index n_{core} which is surrounded in all directions transverse to photon propagation direction by relatively low refractive index medium with refractive index n_{low} to spatially
30 confine photons strongly in all transverse directions perpendicular to their propagation direction.

28. The device of claim 27 wherein said waveguide core has a dimension ds in said transverse direction and dw in said another direction, said dimension ds having a normalized value ds_n larger than 0.05 and smaller than 4.0 where $ds_n = ds/ds_{\text{lambda}}$ with $ds_{\text{lambda}} = \text{Lambda}/n_{\text{eff}}^s$, where lambda is the active-layer emission wavelength in free space (vacuum or in the absence of material medium) and n_{eff}^s is the effective refractive index given by $n_{\text{eff}}^s = \text{Sqrt}(n_{\text{core}}^2 - n_{\text{low}}^2)$, and Sqrt denotes square rooting, said dimension dw having a normalized value dw_n larger than 0.05 and smaller than 1.1 for single-mode guiding and for Beta(space) value, where $dw_n = dw/dw_{\text{lambda}}$ with $dw_{\text{lambda}} = \text{lambda}/n_{\text{eff}}^w$ wherein n_{eff}^w is the effective refractive index given by $n_{\text{eff}}^w = \text{Sqrt}(n_{\text{core}}^2 - n_{\text{high}}^2)$.

29. The device of claim 28 wherein ds is in the width direction and dw is in the thickness direction.

30. The device of claim 28 wherein the ratio of $n_{\text{core}}/n_{\text{low}}$ is larger than about 1.3.

31. The device of claim 28 wherein resonant optical cavity and said photonic-well waveguide form a closed loop cavity, at least a substantial portion of said closed cavity comprising said photonic-well waveguide.

32. The device of claim 31 wherein a plane of said closed loop cavity is parallel to a width

dimension.

5 33. The device of claim 28 wherein said
photonic-wire waveguide comprises an optically
active excitable medium that can give rise to the
radiation or absorption of electromagnetic field
energy, said medium being selected from
semiconductor quantum wells, quantum dots, quantum
wires, rare earth ions, and bulk semiconductor
10 materials.

15 34. The device of claim 28 wherein said
photonic-wire waveguide comprises passive
dielectric material.

20 35. The device of claim 31 in which the
length of the closed loop cavity L_c is microcavity
in dimension with a normalized length L_{cn} of less
than 300.

25 36. The device of claim 35 in which said
microcavity provides a $\text{Beta}(\text{Freq})$ of larger than
0.05 when the emission width from the active
medium is generally frequency width equal to $1/20$
of the optical emission frequency exhibited by
semiconductor quantum wells.

30 37. The device of claim 29 wherein the
normalized width of the photonic-wire waveguide ds_n
is larger than 0.5 and smaller than 1.1 and dw_n is
larger than 0.1 and smaller than about 0.5.

38. The device of claim 37 wherein the waveguide achieves an estimated Beta(space) value of about 0.25 and larger.

5 39. The device of claim 29 wherein the normalized width of the photonic-wire waveguide ds_n is larger than 0.05 and smaller than 4.0, the normalized thickness dw_n is larger than 0.05 and smaller than about 1.1, the ratio $n_{\text{core}}/n_{\text{low}}$ is larger
10 than 2.0.

 40. The device of claim 39 wherein the waveguide achieves an estimated Beta(space) value of about 0.002 to about 0.3.

15 41. The device of claim 28 in which the waveguide comprises semiconductor materials selected from $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$ or $\text{In}_x\text{Al}_{1-x-y}\text{Ga}_y\text{As}$ as the n_{core} and a material with a refractive index of about
20 1.6 or lower comprises the n_{low} material.

 42. The device of claim 41 for operation at 1.1 micron to 1.6 micron wavelength range for which ds is about 0.6 micron or smaller and dw is
25 about 0.3 micron and smaller, with ds being larger than about 0.2 micron and dw being larger than about 0.03 micron.

 43. The device of claim 28 in which the waveguide comprises semiconductor materials selected from $\text{In}_x\text{Ga}_{1-x}\text{N}$ or $\text{Al}_x\text{Ga}_{1-x}\text{N}$ as the n_{core}
30 materials and a material with a refractive index

of about 1.6 or lower comprises the n_{low} material.

5 44. The device of claim 43 for operation at 0.2 micron to 0.7 micron wavelength range for which d_s is about 0.3 micron or smaller and d_w is about 0.3 and smaller, with d_s being larger than about 0.0.04 micron and d_w being larger than about 0.01 micron.

10 45. The device of claim 44 in which the waveguide comprises semiconductor materials selected from $\text{In}_x\text{Ga}_{1-x}\text{As}$ or $\text{In}_x\text{Ga}_{1-x}\text{P}$ as the n_{core} and a material with a refractive index of about 1.6 or lower comprises the n_{low} material.

15 46. The device of claim 28 for operation at 0.6 micron to 1.0 micron wavelength range for which d_s is about 0.4 micron or smaller and d_w is about 0.0.25 and smaller, with d_s being larger than about 0.1 micron and d_w being larger than about 0.02 micron.

20 47. The device of claim 28 wherein said photonic-well waveguide is formed as a closed loop with one or more arcuate shapes, one or more linear shapes, and combinations thereof.

25 48. The device of claim 47 wherein radius of curvature R_i of the arcuate segment is in the range of large curvatures defined by radius of curvature smaller than $50 \lambda / n_{\text{core}}$.

30

49. The device of claim 48 wherein the waveguide width d_s is larger than the lowest-order mode of propagation and at least a portion of an inner rim of said closed loop is roughened to increase scattering loss on higher-order modes.

50. The device of claim 48 wherein the waveguide normalized width d_s is larger than 0.05 and smaller than 100, without affecting the waveguiding of the lowest-order mode significantly, due to the large curvature of the waveguide.

51. The device of claim 28 in which lasing is achieved with said excitable medium excited to achieve population inversion in the photonic-well waveguide.

52. The device of claim 31 in which electromagnetic energy in said closed loop cavity is coupled to the electromagnetic energy in an output-coupled waveguide encircling partially thereabout with a small gap of low refractive index material therebetween.

53. The device of claim 52 wherein the gap is smaller than 10 and larger than 0.02 optical wavelength in the photonic-wire waveguide.

54. The device of claim 53 wherein the modes in the closed loop cavity and the output-coupled waveguide are spatially the lowest-order mode.

55. The device of claim 54 wherein the closed loop cavity and the output-coupled waveguide comprise the same waveguide structure in a thickness direction.

5

56. The device of claim 55 including means for exciting the active medium in the output-coupled waveguide to reduce loss therein or to provide optical gain therein.

10

57. The device of claim 56 wherein the active medium is present only along a partial length of the output-coupled waveguide.

15

58. The device of claim 57 wherein the active medium is not excited beyond population inversion and can be further excited by absorbing photons propagating in the output-coupled waveguide.

20

59. The device of claim 58 wherein said active medium functions as a detector or modulator.

25

60. The device of claim 28 wherein the active medium is not excited beyond population inversion and can be further excited by absorbing photons propagating in the output-coupled waveguide.

30

61. The device of claim 28 wherein said active medium functions as a detector or

modulator.

5 62. The device of claim 28 including means
for optically exciting the excitable medium by
illumination with electromagnetic energy.

10 63. The device of claim 28 including means
for electrically exciting the excitable medium by
carrier injection into said medium using a
semiconductor p-n junction.

15 64. A combination of the device of claim 28
and one or more integrated circuits.

20 65. The combination of claim 64 further
including an optical fiber between said device and
said integrated circuit.

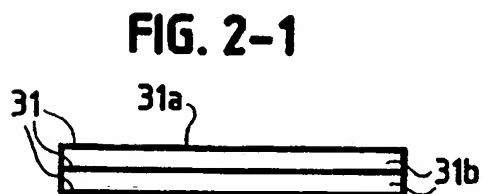
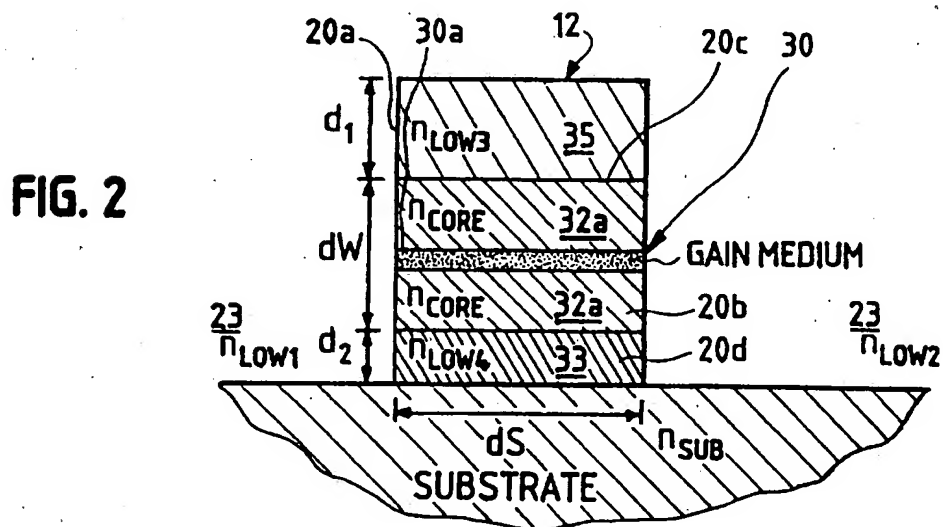
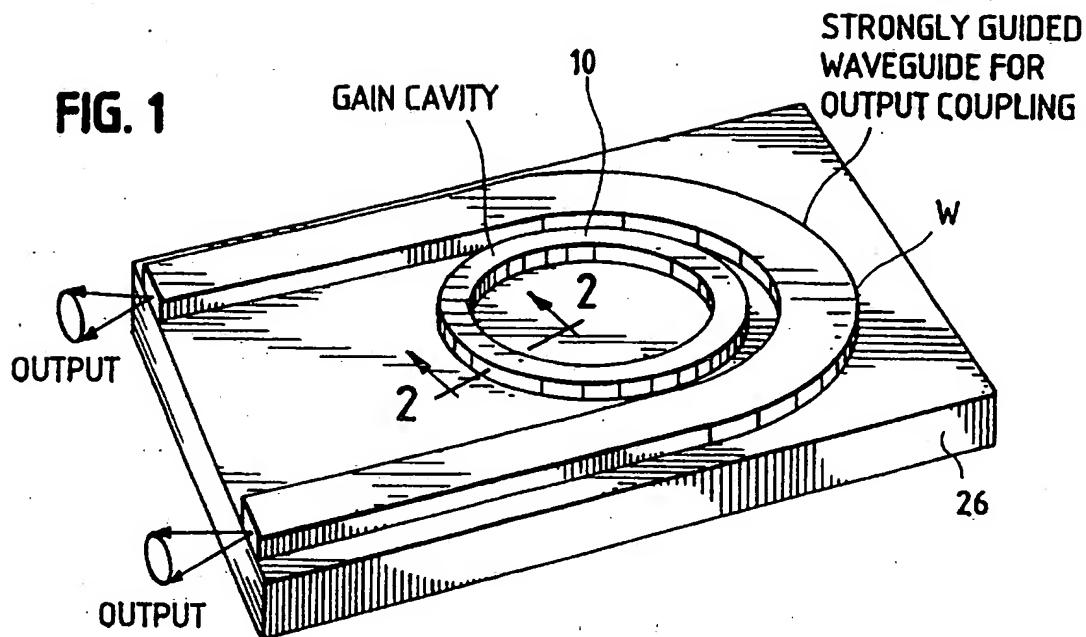
25 66. The device of claim 52 wherein said
cavity is coupled to one or more said output-
coupled waveguides, each serving either as a light
output port, or a light input port, or both a
light output port and input port.

30 67. The device of claim 66 wherein
properties of light in the output port are
dependent on the properties of light in the input
port and the amount of population excitation.

30 68. The device of claim 66 wherein the
properties of light in the output ports and the

properties of light in the input ports are used to process or transform optically coded signals or information.

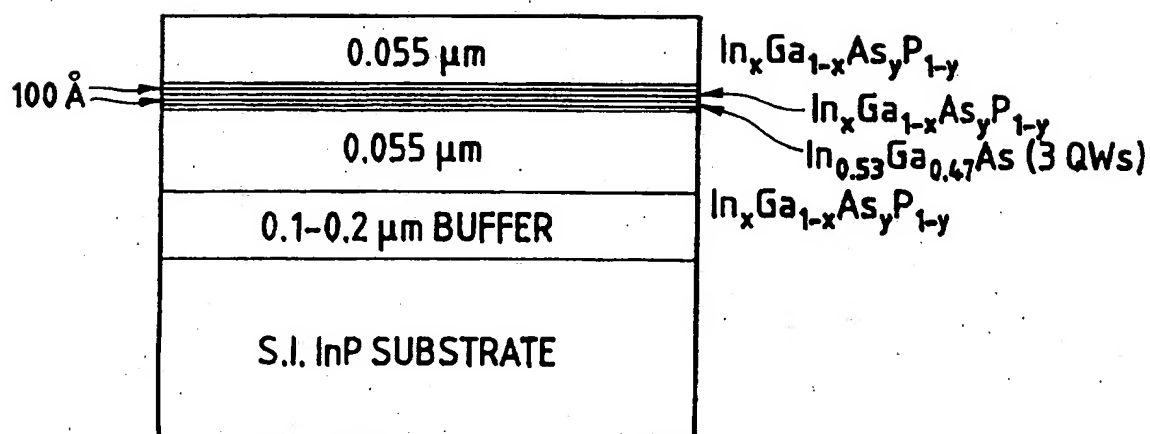
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FIG. 2A



$$x=0.84, y=0.33$$

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FIG. 3

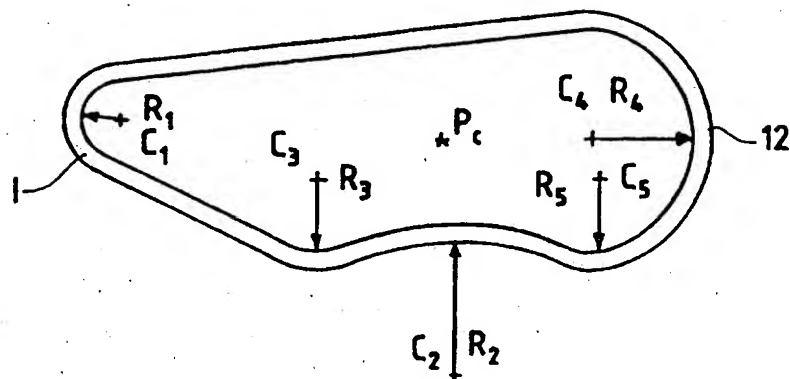


FIG. 4

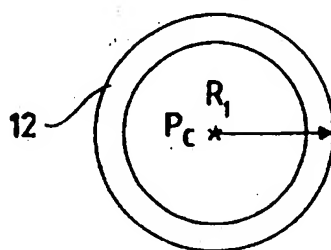


FIG. 5

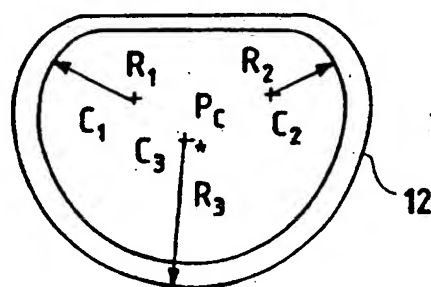
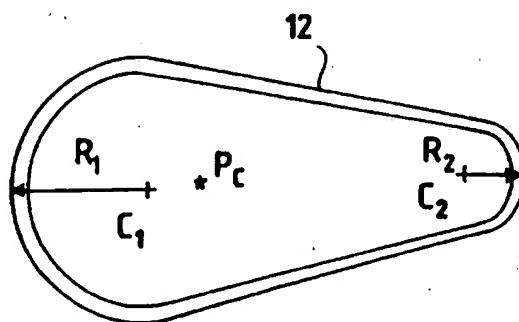


FIG. 6



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FIG. 7

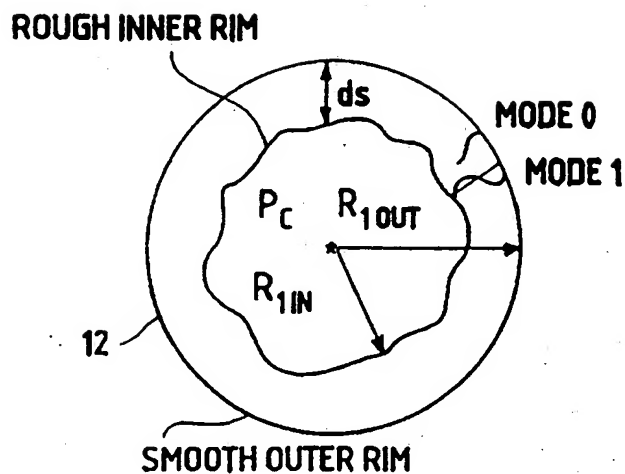


FIG. 7A

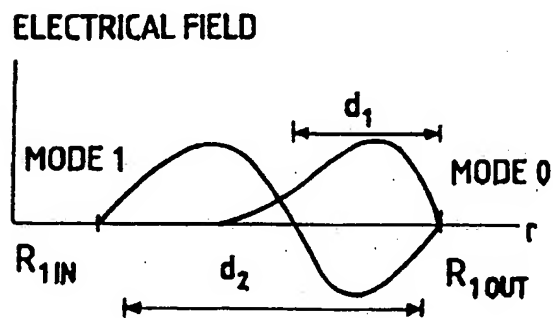
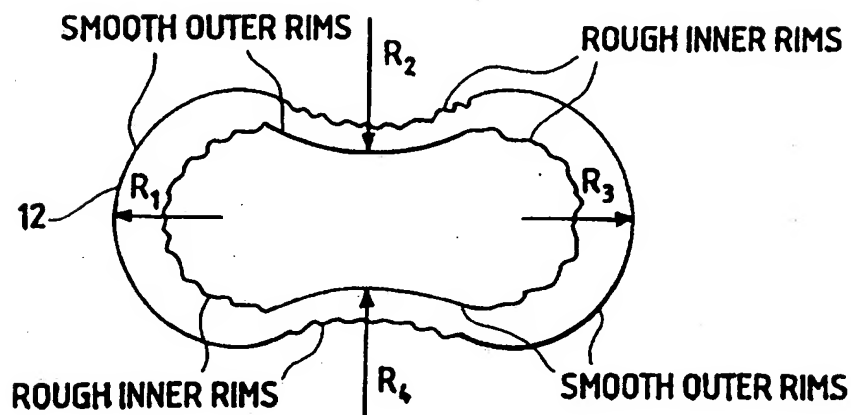


FIG. 8



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FIG. 9

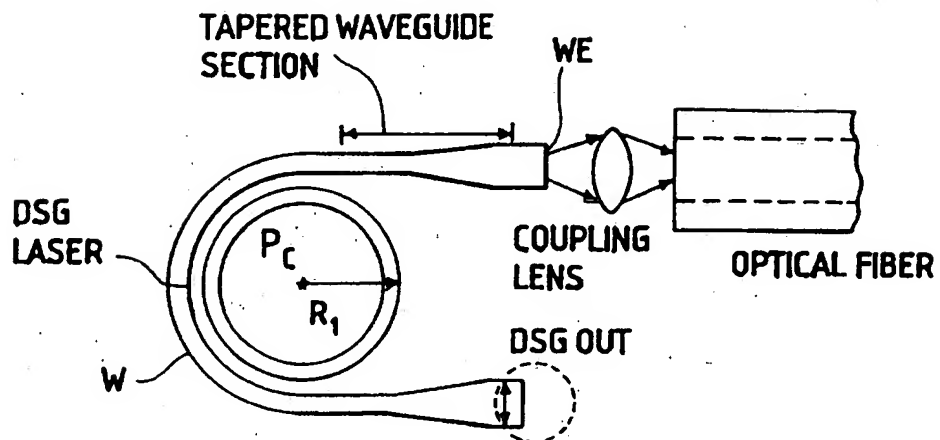
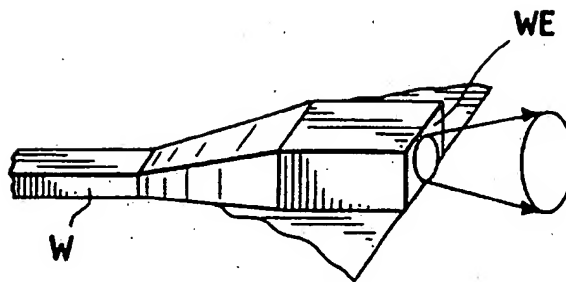


FIG. 9A



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FIG. 10

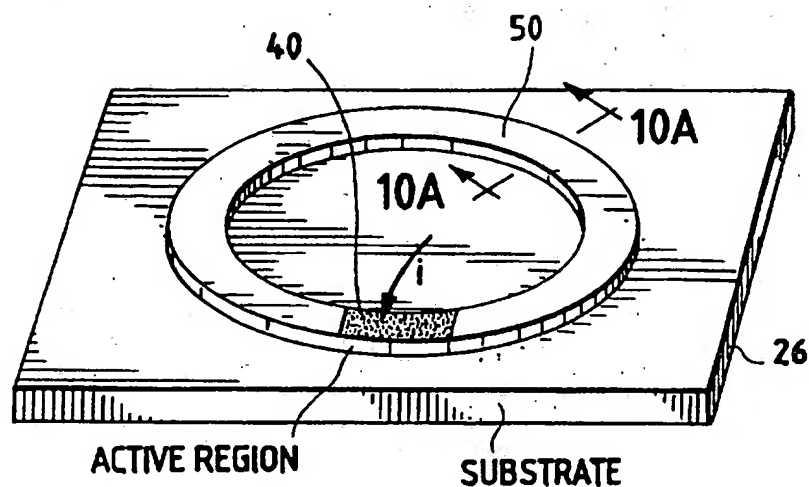


FIG. 10A

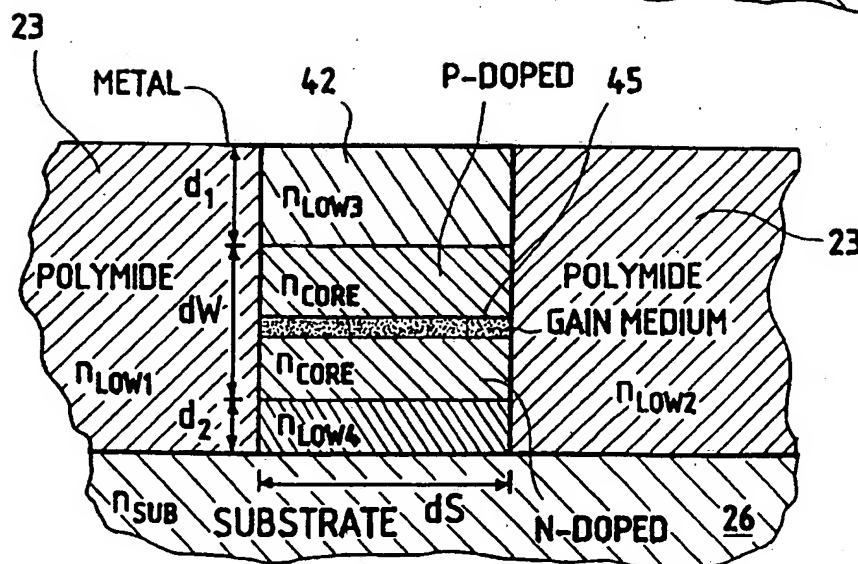
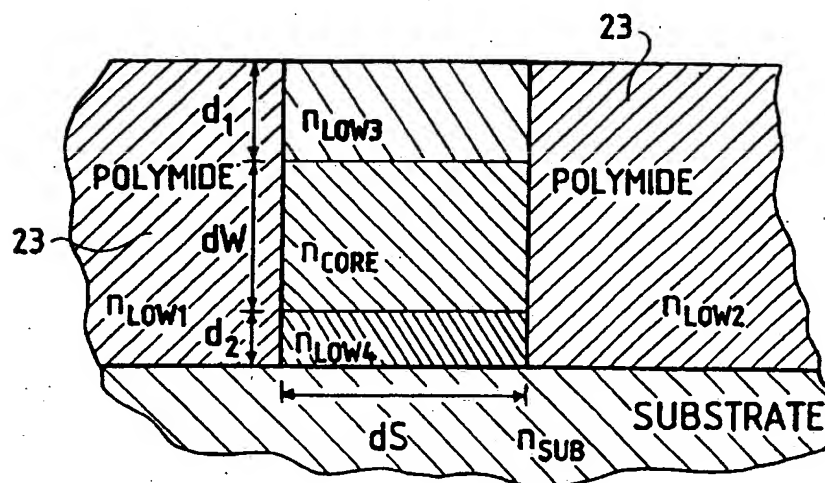


FIG. 10B

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FIG. 11

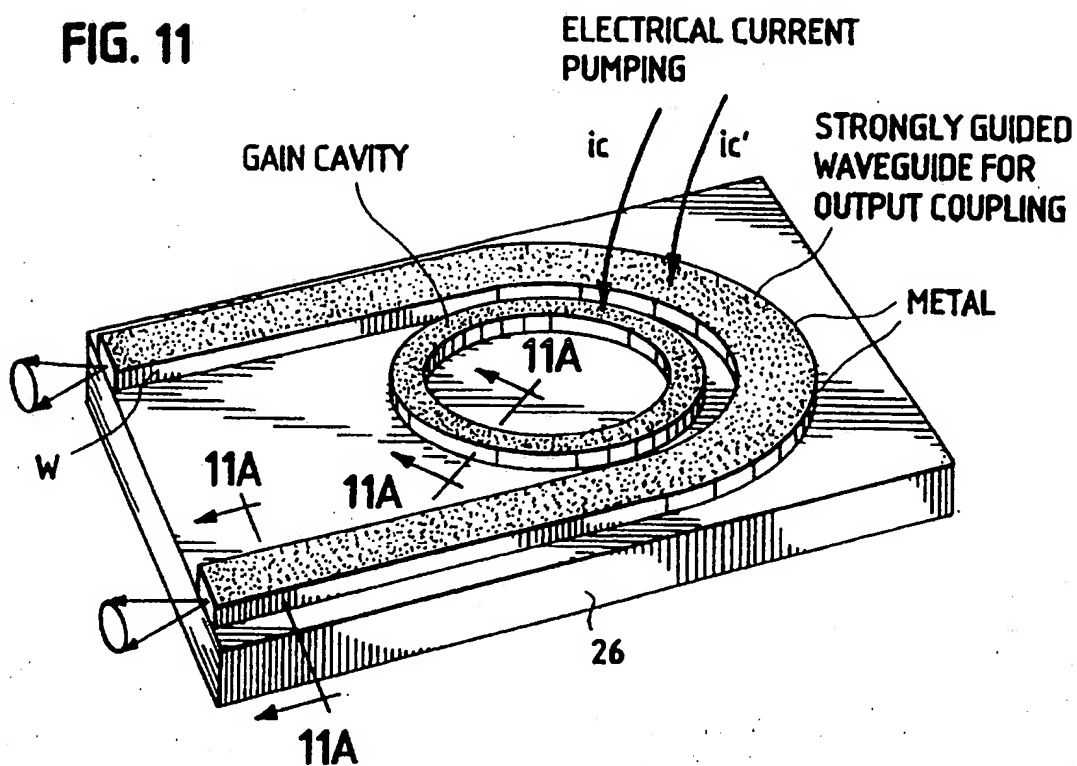
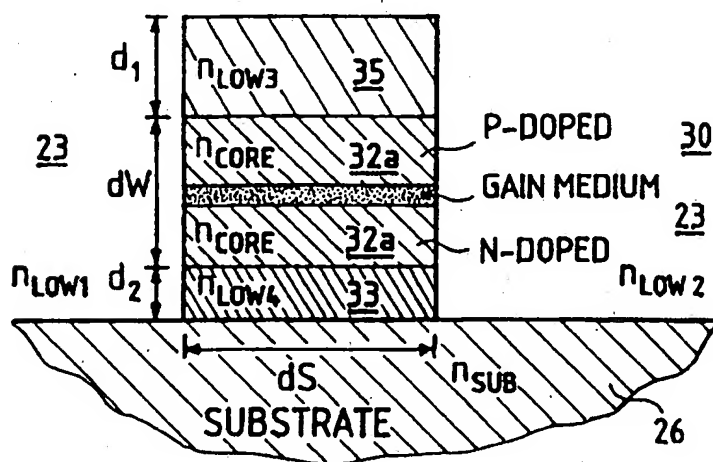


FIG. 11A



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FIG. 12

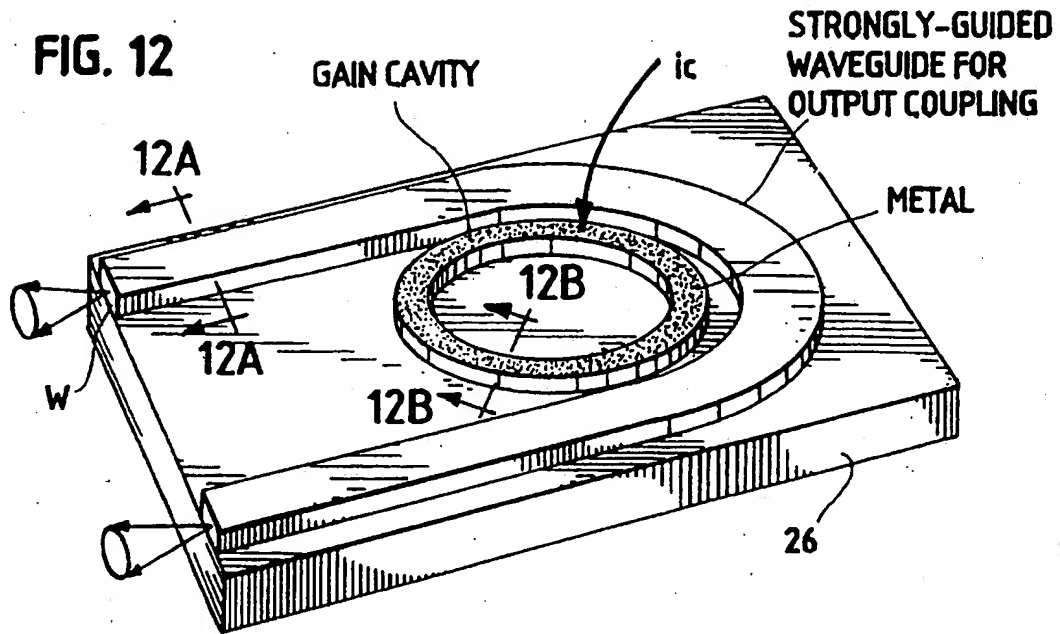


FIG. 12B

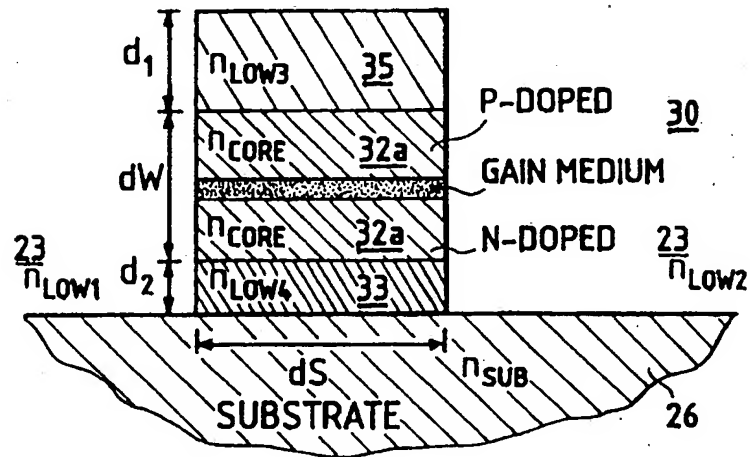
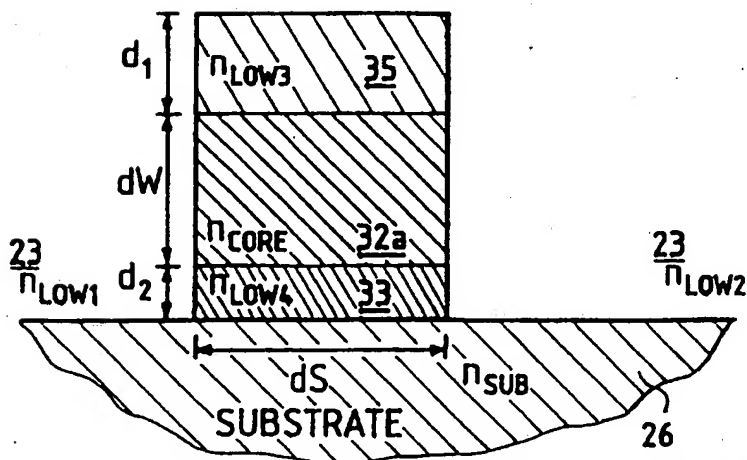


FIG. 12A



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FIG. 13

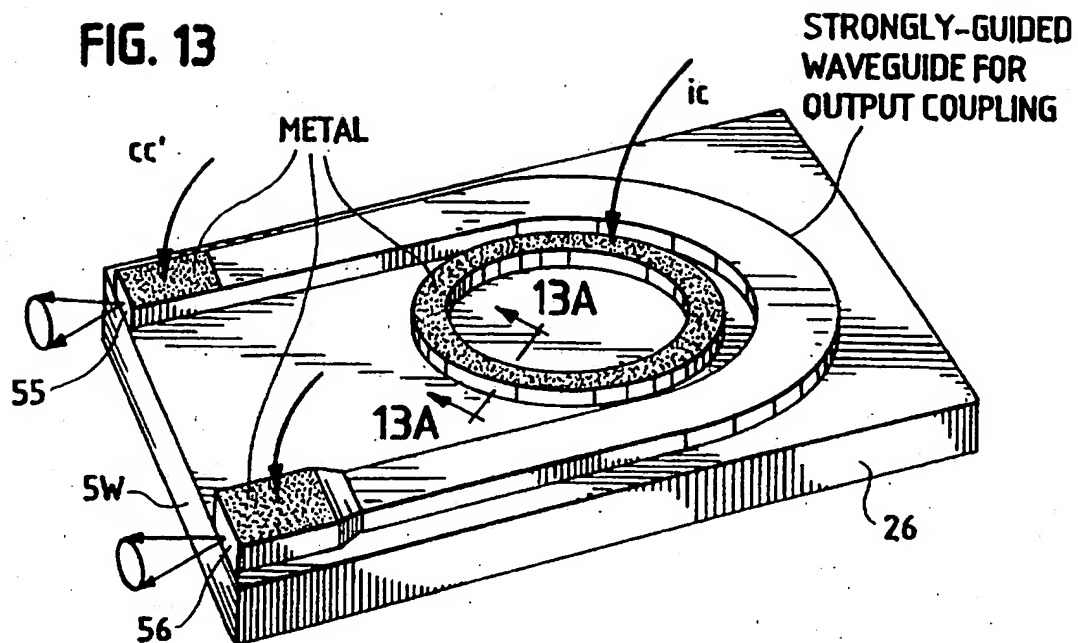
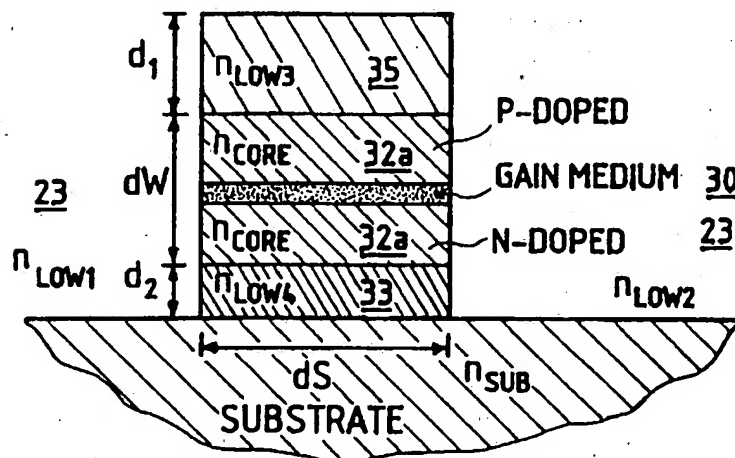


FIG. 13A



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FIG. 14

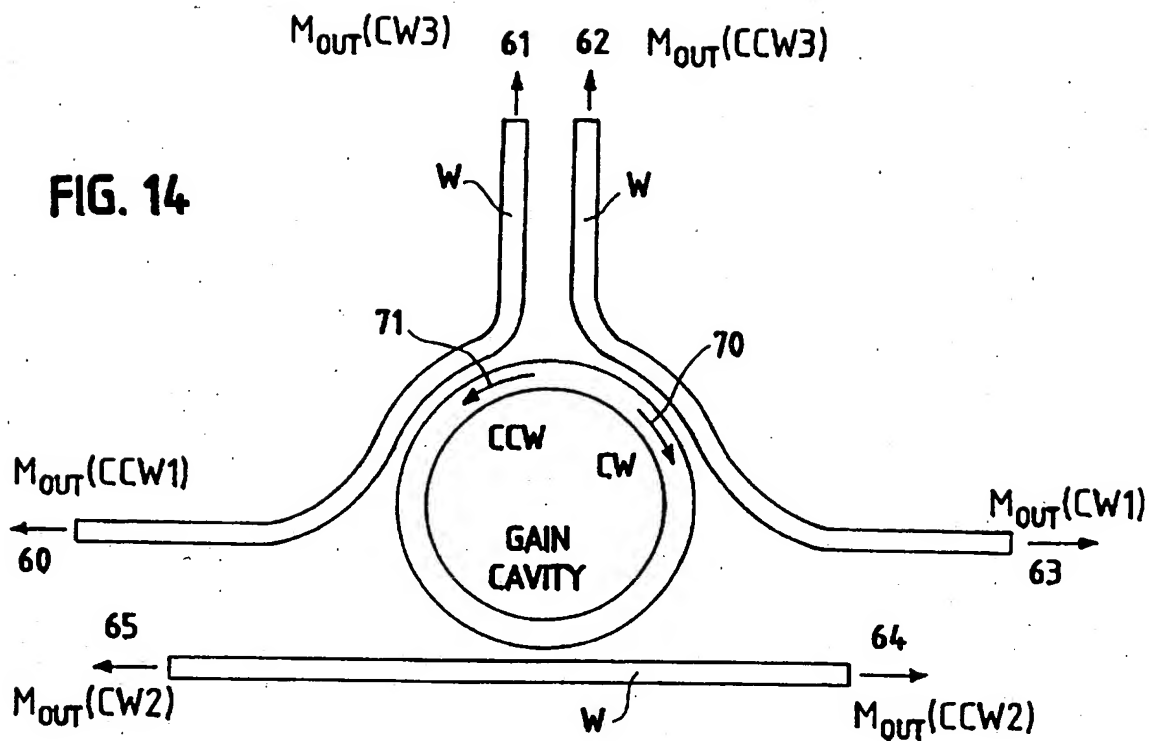
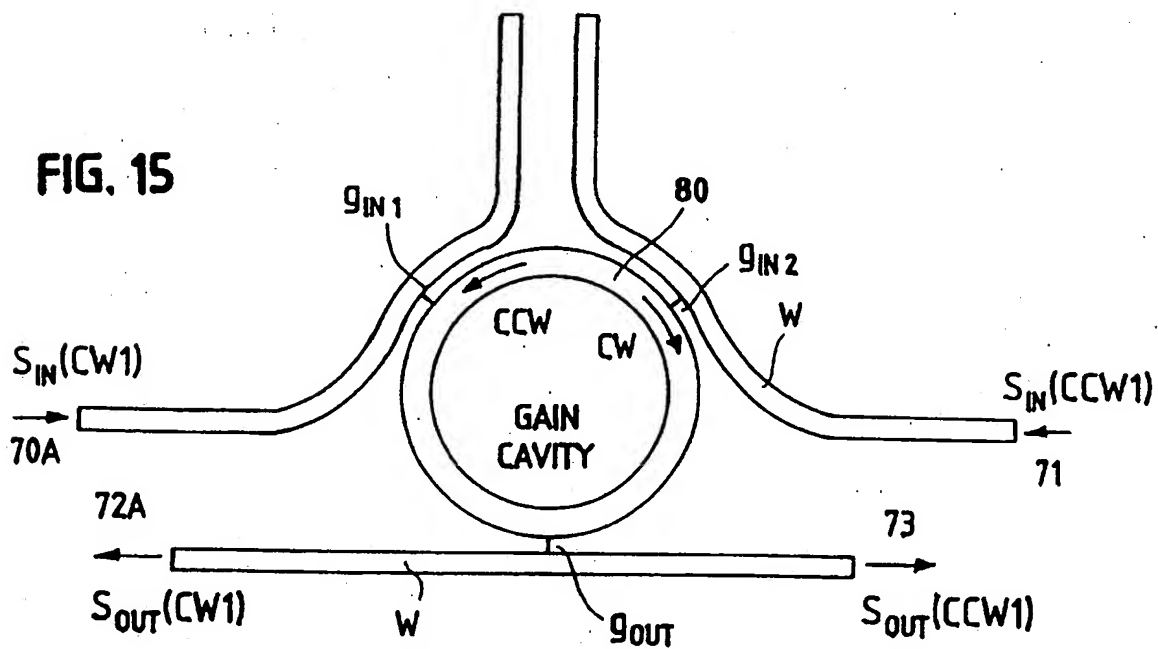
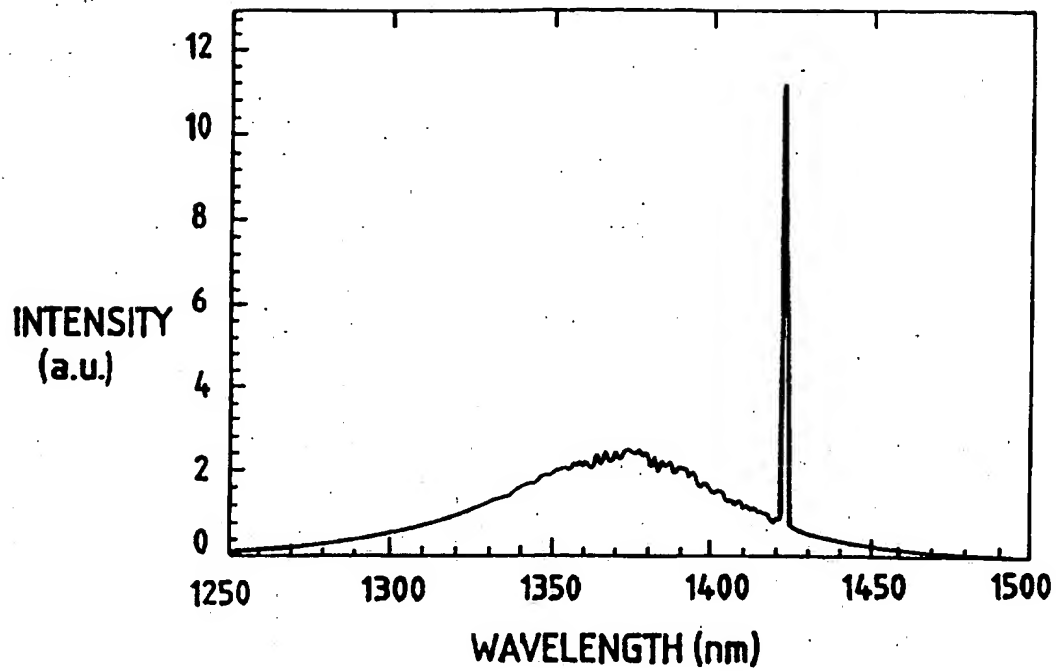
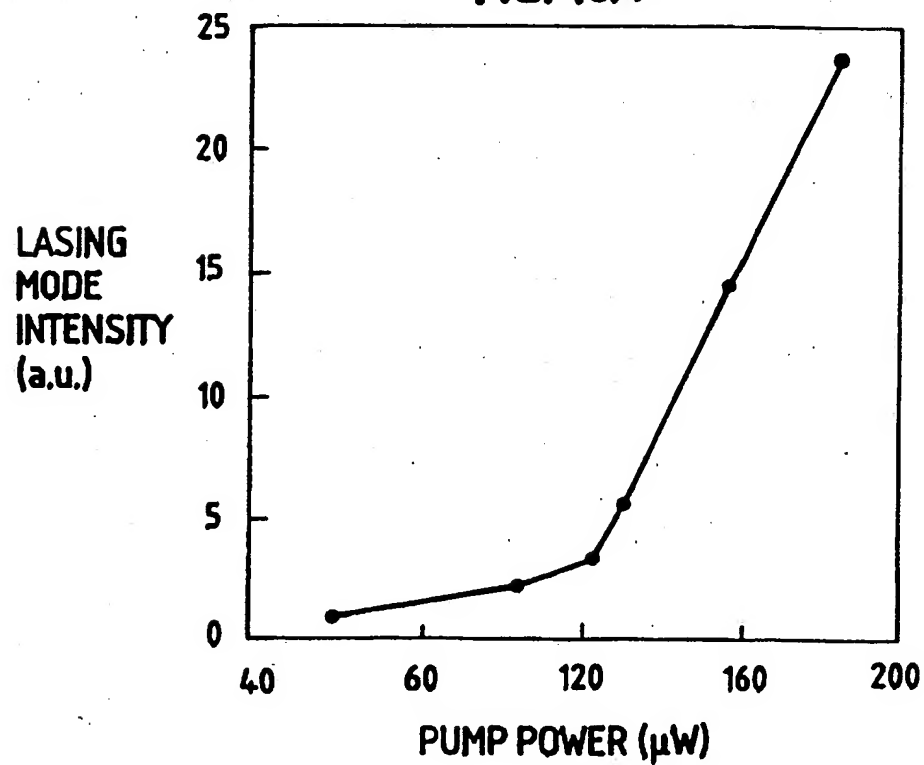


FIG. 15



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FIG. 16**FIG. 16A**

SUBSTITUTE SHEET (RULE 20)

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US97/08744

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : H01S 3/05, 3/08

US CL : 372/108, 104, 66, 67, 92, 94; 385/31, 32, 43

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 372/108, 104, 66, 67, 92, 94; 385/31, 32, 43

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS, DIALOG

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	ZHANG et al. Photonic-Wire Laser. Physical Review Letters. 02 October 1995. Vol 75. No. 14. pages 2678-2681, especially page 2678.	1-5, 10-23
X	CHU et al. Spontaneous Emission from Excitons in Cylindrical Dielectric Waveguides and the Spontaneous-Emission Factor of Microcavity Ring Lasers. J. Opt. Soc. Am. B. February 1993. Vol 10. No. 2. pages 381-390, especially page 386.	1-5, 10-14, 22, 23, 27
Y	US 5,265,177 A (CHO ET AL) 23 November 1993 (23/11/93), see entire document, especially Figure 1.	15-21, 25, 26
Y	US 5,351,261 A (LANZEROTTI ET AL) 27 September 1994 (27/09/94), see entire document, especially Figure 7.	15-21, 25, 26



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:	*T	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
A document defining the general state of the art which is not considered to be of particular relevance	*X*	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
E earlier document published on or after the international filing date	*Y*	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
L document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	*G*	document member of the same patent family
O document referring to an oral disclosure, use, exhibition or other means		
P document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

22 JULY 1997

Date of mailing of the international search report

13 AUG 1997

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Box PCT
Washington, D.C. 20231

Facsimile No. (703) 305-3230

Authorized officer

VIGUN SONG

Telephone No. (703) 305-5437

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/08744

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☒ Claims Nos.: 6-9
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
☐ No protest accompanied the payment of additional search fees.